Understanding Heating Seasonal Performance Factors for Heat Pumps

Paul W. Francisco, University of Illinois, Building Research Council
Larry Palmiter and David Baylon, Ecotope, Inc.

ABSTRACT

The heating and cooling efficiencies of residential heat pumps are often characterized by a single number for each mode. These values are determined at specific test conditions. For heating, this rating is referred to as the HSPF (Heating Seasonal Performance Factor), and for cooling (for both heat pumps and air conditioners) the rating is the SEER (Seasonal Energy Efficiency Ratio). These values are used by consumers to compare conditioning systems, by utility program managers and regulators to predict savings and establish incentives, and by designers to specify equipment.

The seasonal performance factors are also often used to predict annual energy use and potential savings from equipment upgrades. However, the actual performance of the equipment depends on a variety of factors, including the climate in which it is being used and the heat loss rate of the building. Furthermore, the overall energy use (and seasonal performance) can be greatly impacted by factors such as equipment sizing, control strategy, and duct losses.

This paper presents the results of a review of the industry standard HSPF calculation procedure. This review included consideration of the impacts of climate and building load on the actual seasonal performance, as well as an investigation into the standard algorithm itself. This investigation found several inconsistencies between the standard and actual heat pump and building performance, such as the calculation of building load, the generation of heat pump performance data, and the use of defrost. The results show that the HSPF rating is inappropriate for many locations, and thus can not be used to estimate energy use or savings. They also show that the calculations can be significantly impacted by the method in which the building load is calculated, as well as by the performance data and degradation coefficients used.

Introduction

The heating performance of unitary air-source heat pumps is typically represented by the Heating Seasonal Performance Factor (HSPF). The HSPF is a single value that is intended to represent the overall efficiency of the heat pump for the entire heating season, and is the ratio of output capacity in BTU/hr (Btuh) to power input in watts. The standard method by which the HSPF is determined is provided by the Air-Conditioning and Refrigeration Institute (ARI 2003).

This standard describes the range of conditions to be evaluated, including six different climate zones and several different building loads. However, the official published HSPF rating is from a single climate zone (IV) and building load (minimum expected for the heat pump).

This opens up the possibility for misuse of the rating as a means to predict energy consumption or savings. One example of this is the HERS rating, which includes the ratio of the HSPF of the rated building's heat pump to the HSPF of the reference building's heat pump (National Association of State Energy Officials 2000). This implies use of the HSPF to calculate the energy use for each building, and assumes that a percentage increase in HSPF corresponds directly to the same percentage reduction in energy use.

Another example of how the published HSPF is used to estimate savings from changes in equipment is the Retrofit Guide produced by Oak Ridge National Laboratory (Wendt et al. 1996). This document provides guidance on assessing energy conservation opportunities to retrofit program managers. For heat pumps, the Retrofit Guide includes a figure that shows the savings for a variety of HSPF improvements as a function of heating degree days (HDD) using a temperature base of 65 F. However, the HSPF calculation is based on the distribution of the annual load in temperature bins. Locations that have long, cool seasons, such as is common along the west coast of the United States, may have comparable HDD to other locations with shorter but colder heating seasons, but very different heat pump seasonal performance. For example, TMY2 (Typical Mean Year, series 2) data shows Seattle as having 4867 HDD, which is similar to those for St. Louis (5021) and New York City (5090). However, since Seattle has a long, mild winter rather than a shorter but colder winter, the impact of improving the efficiency of a heat pump will be very different than it would be in either St. Louis or New York.

The use of HSPF for predicting energy use or savings recently prompted the authors of this paper to review the HSPF calculation procedure. This included both the impacts of climate and building load and the actual calculation algorithm in the ARI standard. This paper presents several of the important findings from this review, and provides insight into the limitations of using a single value to describe the heating performance of heat pumps. This paper is limited to single-speed heat pumps. Issues relating to duct losses, control strategies, and equipment oversizing were presented in a previous paper (Francisco et al. 2004) and are not discussed here.

Examined Aspects of the HSPF Calculation

Several different portions of the HSPF calculation procedure were examined. These include the effect of climate, the effect of different house heating requirements, the use of a default degradation coefficient, the "C-factor" of 0.77, and the effect of the calculated performance curve compared to the manufacturers' published data.

The first two of these, the effects of climate and house heating requirements, are part of the HSPF calculation procedure. However, since only the results from a single climate zone and heating requirement are used for the nominal HSPF, it is worth examining the extent to which the use of different assumptions deviates from the published value.

Degradation Coefficient

The calculation procedure for HSPF requires testing that obtains the heat pump degradation coefficient. However, this degradation coefficient is not published, and is therefore unavailable to anyone wishing to perform the standard calculation on an existing unit using manufacturers' data. It would therefore be required to assume a value. For cooling, the ARI standard allows a default value of 0.25, which agrees with the recommendation of McQuiston and Parker (1988) when a different value is not available.

This is an issue because improvements to equipment have resulted in typical degradation coefficients being much smaller than 0.25, resulting in greater efficiency. In any case, it is of interest to examine the importance of the degradation coefficient on HSPF.

Using manufacturers' data, it is possible to back out a calculated degradation coefficient on the cooling side if performance data for the indoor condition of 80 F dry bulb / 67 F wet bulb is given. The ARI standard provides the following two equations:

$$PLF(0.5) = 1 - 0.5 \times C_d \qquad \text{and} \qquad SEER = PLF(0.5) \times EER_B \tag{1}$$

where $PLF(0.5)$ is the part load factor with a cooling load factor of 0.5
C_d is the degradation coefficient
$SEER$ is the published seasonal energy efficiency ratio
EER_B is the energy efficiency ratio at 80 F indoor dry bulb, 67 F indoor wet bulb, and 82 F outdoor dry bulb

EER_B can be calculated by dividing the output capacity at the specified indoor conditions, in kBtuh, by the energy input required in kW. The degradation coefficient is then

$$C_d = 2 * \left(1 - \frac{SEER}{EER_B}\right) \tag{2}$$

It is likely that the degradation coefficient on the heating side is slightly higher, but the extent to which this is true is not clear. Data are not available that would allow the calculation of a degradation coefficient on the heating side. Therefore, in this study, the effect of the measured degradation coefficient was evaluated using the values estimated from cooling data.

"C-Factor"

The standard HSPF calculation procedure includes the use of a multiplier, called the "C-factor", that is applied to the building load at each bin. The rationale for this, as stated in the ARI standard, is that the use of the C-factor causes the calculated annual loads to more accurately match measured annual loads. The value of the C-factor is 0.77. The building load calculation in the standard calculation procedure is

$$BL(T_i) = \left(\frac{65 - T_i}{65 - T_{OD}}\right)(C)(DHR) \tag{3}$$

where $BL(T_i)$ is the building heating load in Btuh at temperature bin T_i in degrees F
T_{OD} is the design outdoor temperature for the climate zone of interest, F
C is the C-factor of 0.77
DHR is the design heating requirement used in the calculation, Btuh. The DHR calculation uses an indoor temperature of 65 F.

The primary reason that the calculated building load without the C-factor does not match measured building loads is because of heat gains to the home combined with thermal storage by the building materials. These gains come in multiple forms, including solar gains as well as internal gains from such sources as lighting, appliance heat, and occupants. However, the implication of the C-factor that the gains account for 23% of the heat required at every temperature bin is incorrect. Rather, the gains change the “house heating balance point”, which is the outdoor temperature at which heating is required. Gains are effectively a heat source that can meet a certain load.

The problem with applying the C-factor to heat pump performance evaluation was recognized by ASHRAE as far back as 1985 (ASHRAE 1985). In the Handbook of Fundamentals, it is stated that the C-factor (referred to as C_D in the Handbook) was developed to account for the fact that a balance point of 65 F was no longer an appropriate base due to the increased use of insulation. Further, the Handbook discusses the variable base degree day method, which accounts for the impact of gains by adjusting the balance point. This version of the Handbook also discusses the bin method for calculating energy use, which was developed in part to better estimate the energy use of heat pumps. This method “gives credit for internal loads by adjusting the balance point.” In an example, the gains are represented by an average value.

Erbs et al. (1986), in a review of the ARI procedure for rating variable speed heat pumps, state that the balance point at the time was often 55-60 F. Since more current construction often has greater insulation and better windows than in the mid-80s, the typical balance point range can probably be expanded to 50-60 F. Note that this balance point is not the compressor balance point, which is the temperature at which the heat pump can exactly meet the building load without backup. In this paper, the term balance point will always refer to the house heating balance point unless otherwise specified.

In this study, a set of HSPF calculations was done with the C-factor removed and the balance point changed to 55 F, which was also the recommendation of Erbs et al (1986). These were compared to the results with the balance point kept at 65 F and the C-factor kept at 0.77, as stipulated in the standard HSPF calculation procedure. The equation using the balance point T_{bal} instead of the C-factor can be written as

$$BL(T_i) = \left(\frac{T_{bal} - T_i}{65 - T_{OD}} \right) (DHR) \tag{4}$$

The left panel of Figure 1 shows the difference in building load between these two calculation techniques. This figure looks similar to a figure in the Erbs et al. paper. The heat pump capacity is based on the manufacturer’s data for the high-efficiency 3-ton unit used in this study. The building load assumes the minimum *DHR* for climate zone IV. The right panel shows the effective heat gains for the two calculation methods.

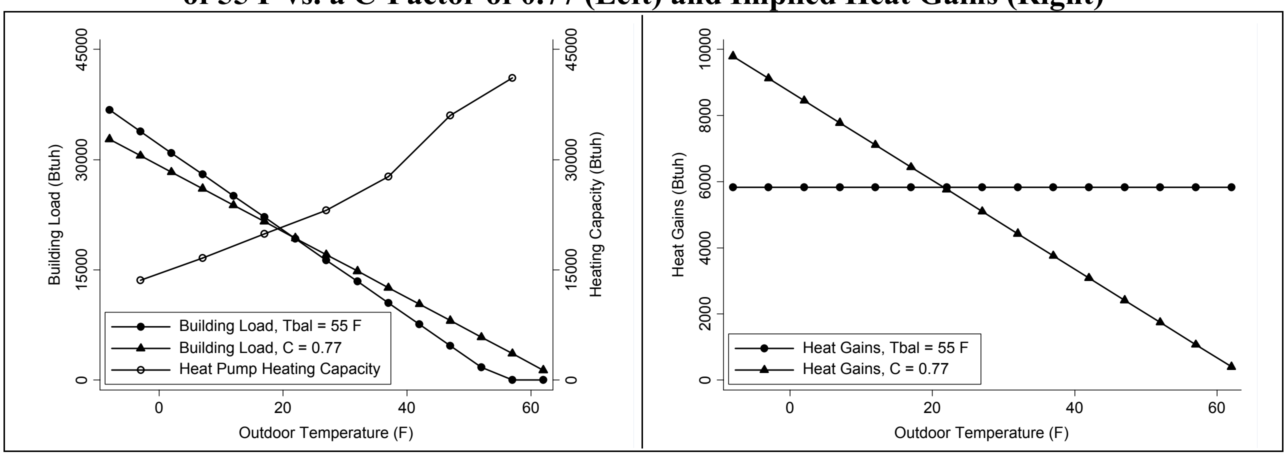
This graph shows that, above an outdoor temperature of about 22 F, the use of a balance point produces a lower building load, including no load at the warmest two bins. Below 22 F, the 23% reduction in building load caused by the use of the C-factor is a greater reduction of the building load than the effect of the balance point.

The right panel shows that the heat gains are considered constant with the balance point technique. This is not completely accurate, since many gains change throughout the day. Solar gains only occur during the day, gains from occupants vary, etc. However, thermal storage tends to reduce the diurnal variation. Further, the use of the C-factor implies heat gains that are less-consistent with diurnal variations. The largest heat gains are at the coldest temperatures, which might reasonably be expected to be at night. At warmer temperatures, at least some hours of which occur in the day when solar gains are occurring, the heat gains are less.

The impact that this has on energy use can be significant. The balance point reduces the amount of time that the compressor operates during temperatures at which the compressor efficiency is highest. At colder temperatures, the balance point calculation method increases the amount of the less-efficient backup heat required. The amount of backup heat required at each bin is represented by the difference between the building load and the heat pump heating capacity whenever the capacity is less than the building load. In this graph, backup heat is required below about 20 F, making that temperature the heat pump compressor balance point.

It is worth noting that the *DHR* is rounded to the nearest standardized value provided in the standard. These standardized values are in 5000 Btuh increments up to 40000 Btuh, after which they are in 10000 Btuh increments up to 110000 Btuh. Without this rounding, the building heat loss rate (UA, which is the heating load divided by the indoor-outdoor temperature difference) in the ARI calculation is the same for all climates except for zone V. For example, the standard states that the minimum *DHR* is the heat pump capacity at 47 F. The equations in the standard then imply that UA is the *DHR* divided by 60 except in zone V, where the UA is the *DHR* divided by 75. A heat pump with a 36000 Btuh capacity at 47 F would lead to a UA of 600 Btuh/F in all climate zones except for zone V, where the UA would be 480 Btuh/F. For the maximum *DHR* the UA is multiplied by 2 except in zone V, where it is multiplied by 2.2.

Figure 1. Example Comparison of Building Load Using a Balance Point of 55 F vs. a C-Factor of 0.77 (Left) and Implied Heat Gains (Right)



Calculated vs. Manufacturer's Performance Data

In the standard HSPF calculation procedure, the capacity and power input curves are generated using measured data from three points. These points are at outdoor temperatures of 47 F (the high temperature test), 17 F (the low temperature test), and 35 F (the frost accumulation test). For the 17 F point, the test is done under conditions that prevent frosting, such that no penalty is to be taken for a defrost cycle.

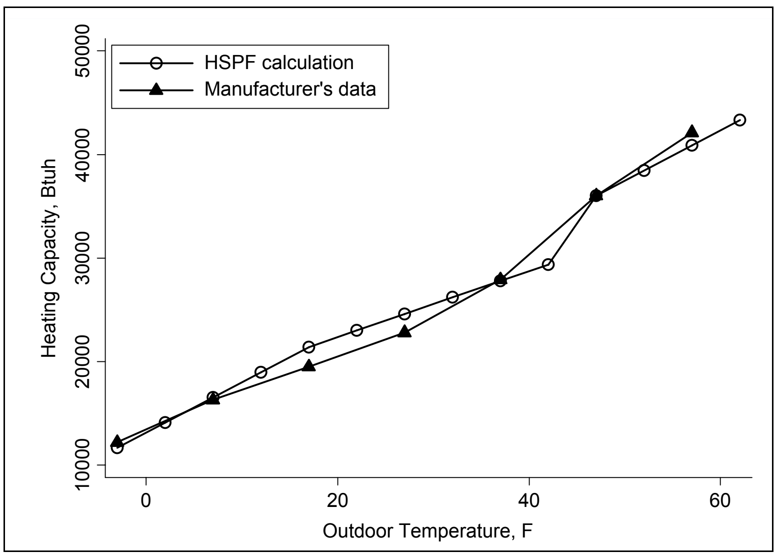
For temperatures at or above 45 F and at or below 17 F, the performance curve is determined by drawing a straight line through the total heating capacities (i.e. no defrost penalty or crankcase heating) at these two temperatures and extending this line to the warmest and coldest temperatures. For temperatures between 17 F and 45 F, the performance curve is determined similarly, but using the measured data at 35 F from the frost accumulation test in conjunction with the 17 F data, rather than the 47 F data.

The 35 F data is not typically available from manufacturers. However, there is an equation in the standard for determining these values for variable speed equipment. Using this equation provided close agreement with the defrost penalty for the heat pumps used in this study, although there are other units for which this did not hold true.

Figure 2 shows a comparison of the performance curve as calculated from the HSPF standard calculation procedure and the manufacturer's data for the higher-efficiency heat pump. The manufacturer's data does include a defrost penalty for temperatures of 37 F and lower, which represents the typical operation of current heat pumps.

This graph shows that the performance data from the HSPF calculation procedure is made up of three straight lines. The use of the total heating capacity at 17 F, without a defrost penalty, results in underestimating the heating capacity above 47 F. There is then a large penalty at the 42 F bin, followed by an overestimate of heating capacity between 7 F and 37 F. Below about 2 F the calculation procedure again underestimates the heating capacity of the equipment.

Figure 2. Example Comparison of Performance Data from HSPF Calculation Procedure to Manufacturer's Data



Methodology

In order to evaluate these issues, the ARI standard calculation procedure was programmed into a computer, with the flexibility to consider the modifications described previously. Two heat pumps were chosen from a single manufacturer. Each has a nominal capacity of 3 tons. One is a high-efficiency unit, with a nominal HSPF of 9.0, while the other is a standard efficiency model, with a nominal HSPF of 7.2. Equations 1 and 2 resulted in calculated degradation coefficients of 0.06 and 0.14 for these two units, respectively.

Calculations were done for all six climate zones, and for the minimum and maximum design heating requirement, rounded as described by the standard. The one exception to this was the investigation of the impact of using calculated vs. manufacturer's performance data. These runs were not done in climate zone V, which has temperatures down to -23 F, because significant extrapolation of manufacturer's data would have been required. Climate zone VI is also not shown in the results section with regard to this specific aspect of the calculation for ease of reading the graphs. The calculated HSPF values for zone VI are similar to those for zone I.

Results

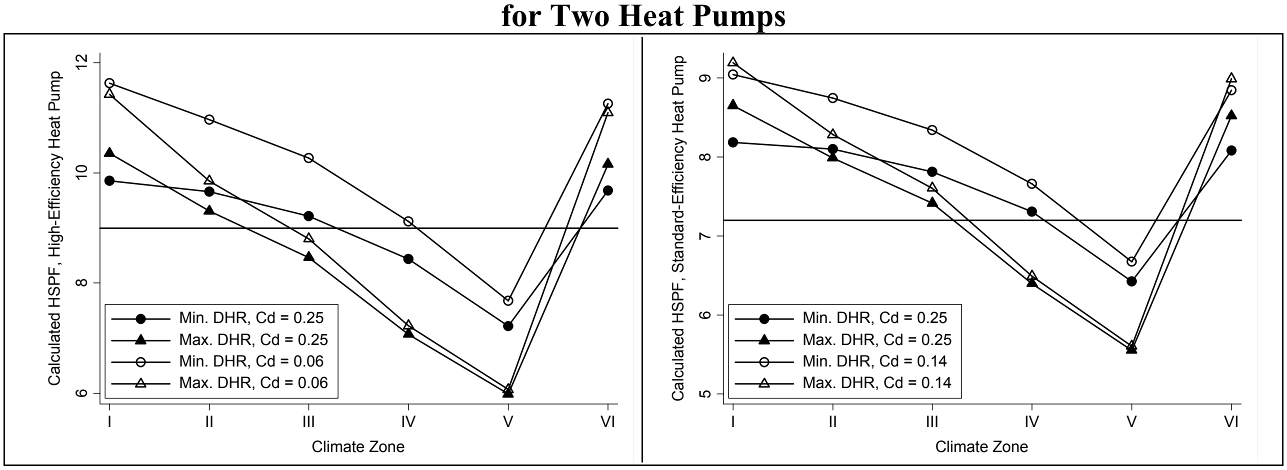
In the following results discussion, most of the graphs will show the effects of climate and building load, along with one of the other aspects investigated. Though the connecting lines do not imply that a climate zone could be added by following the trend, they are included to make it easier to follow the combination of factors for a qualitative comparison across climates. The y-axes are scaled for the unit investigated to allow for the maximum detail.

Climate, Building Load, and Degradation Coefficient

Figure 3 shows the effects of climate, building load, and degradation coefficient on the HSPF for each of the two heat pumps. All of these cases use the C-factor of 0.77 and the performance data calculated using the standard algorithm. The curves marked with hollow circles (minimum *DHR*, measured degradation coefficient) represent the procedure specified by the ARI standard. The fact that the data point in climate zone IV for the standard-efficiency unit using these assumptions does not match the nominal HSPF of 7.2 suggests that one or more assumptions about the inputs to use are incorrect. Both the degradation coefficient and the calculation of the defrost penalty were checked, and neither of these explains the discrepancy. This is an example of the difficulty of replicating the HSPF using available data. For the higher-efficiency unit, the result for this particular condition matches the nominal HSPF fairly well.

There are several interesting features of these graphs. The cases that use the minimum building load change much more gradually than those with the maximum building load. In climate zone I, the HSPF is actually higher with the maximum load than with the minimum load in most cases, but the HSPF with the maximum load drops quickly as the climate gets colder, to the point that it is about a full rating point lower than the minimum load in climate zone V.

Figure 3. Effects of Climate, Building Load, and Degradation Coefficient for Two Heat Pumps



Note: The horizontal line is the nominal HSPF.

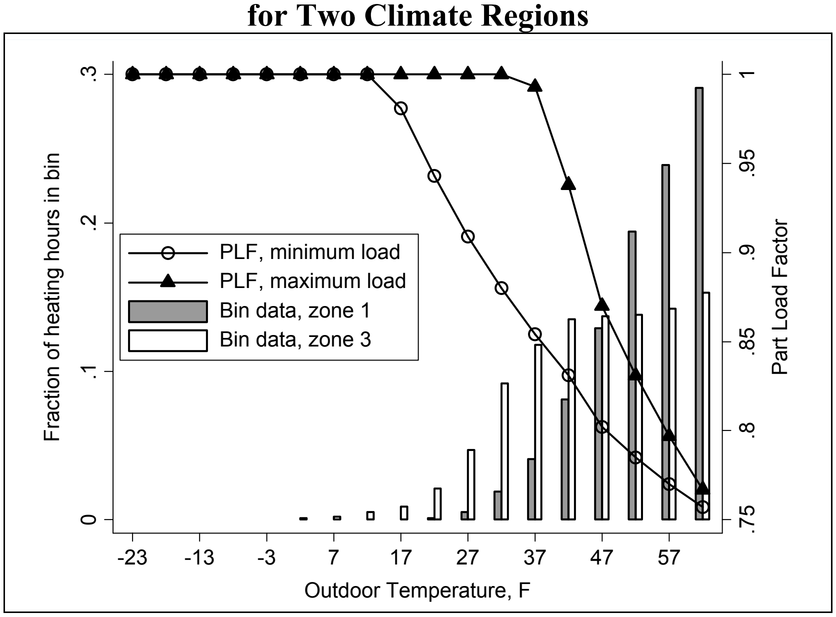
Even for the minimum load case, which shows a more gradual change across climates, the calculated HSPF values can vary by 3-4 rating points from zone I to zone V. Zone VI (predominantly the west coast), despite having many more hours of operation than zone I (predominantly the south), has a similar HSPF because the heating season tends to be very mild.

Using the measured degradation coefficient instead of the default of 0.25 improves the HSPF, meaning that the default underestimates the performance. The impact is large in the warmer climate zones, but is significantly smaller in the colder climates. This is because the heat pump runs for a larger fraction of the time in the colder climates. Since the degradation coefficient is an indication of the losses under part-load operation, it has less impact under these conditions. For the maximum building load in climate zone V, there is almost no difference between using the default degradation coefficient and the one based on manufacturer's data.

It may come as a surprise that the HSPF can be higher in some zones for the maximum building load than the minimum building load. Figure 4 shows why this is the case. This figure shows the part load factor (PLF) for each building load, assuming $C_d = 0.25$, and the bin data for climate zones I and III. A part load factor of 1 indicates that the heat pump is running continuously and backup heating is on. The minimum part load factor is $1\text{-}C_d$.

Because the heat pump needs to run for longer periods of time in the home with the maximum load, the part load factor is closer to 1 at each bin than for the minimum load until the heat pump needs to run continuously even with the minimum load. This means that the efficiency at these warmer bins will be greater with the maximum load. Once the heat pump is running continuously, the overall efficiency decreases because of the less efficient backup heat.

Figure 4. Part Load Factors for Two Building Loads, with Temperature Bins for Two Climate Regions



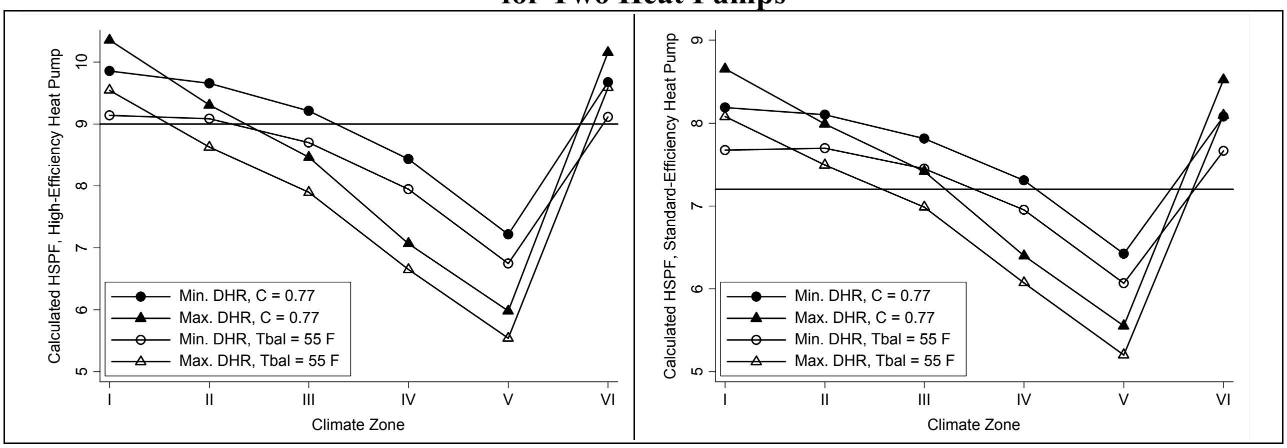
The bin data for the two climate zones shows that the heat pump in climate zone I is operating almost entirely under part-load conditions, even with the maximum load. Therefore, the improvement in the part load factor translates into a higher HSPF with the maximum load than with the minimum load. In climate zone III, however, the heat pump operates for a significant fraction of the time with backup heat for the building with the maximum load, which offsets the improvement at the warmer bins and results in a lower HSPF than for the building with the minimum load. This is exacerbated in colder climates.

C-Factor vs. Balance Point

Figure 5 compares the effect on HSPF of using a balance point instead of the C-factor to adjust the annual energy use for each of the two heat pumps. All of these cases use a default degradation coefficient of 0.25 and the performance data calculated using the standard algorithm.

Contrary to the effect of using a more accurate degradation coefficient, the use of a balance point reduces the HSPF. This means that the use of the C-factor overestimates the HSPF. This effect would be smaller for higher balance points, because a higher balance point allows the heat pump to run for longer at temperatures at which the efficiency is high. For the balance point of 55 F, the decrease in HSPF ranges from about 0.25-1 rating points.

Figure 5. Effect on HSPF of Using the C-Factor vs. a Balance Point for Two Heat Pumps



Note: The horizontal line is the nominal HSPF.

Calculated vs. Manufacturer's Performance Data

Figure 6 compares the effect on HSPF of using the heat pump performance data calculated using the standard vs. the manufacturer's data for each heat pump in zones I through IV. All of these cases use the default degradation coefficient of 0.25 and the C-factor of 0.77.

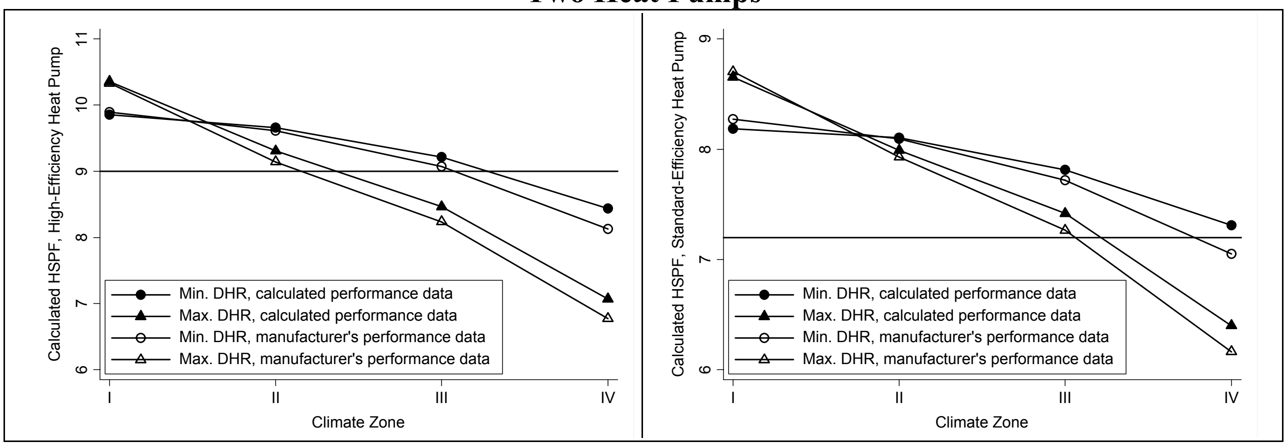
These graphs show that there is little difference between the two in climate zone I, but that for all other climates the calculation procedure overestimates the HSPF compared to the results that would be obtained using manufacturer's data. The effect is not large, with a maximum discrepancy of about 0.3 rating points in climate zone IV. This suggests that the discrepancies shown in Figure 2 largely cancel out over the course of a season.

Combined Effects

Figure 7 shows the effects of combining the measured degradation coefficient and the balance point of 55 F, compared to the calculation using a default degradation coefficient and the C-factor. The difference in performance data is not included, both because it was not calculated for all climate zones and because it is a smaller effect. For comparison, the curve representing the calculation specified by the ARI standard (minimum DHR, measured degradation coefficient, and a C-factor of 0.77) is also shown, denoted by X's.

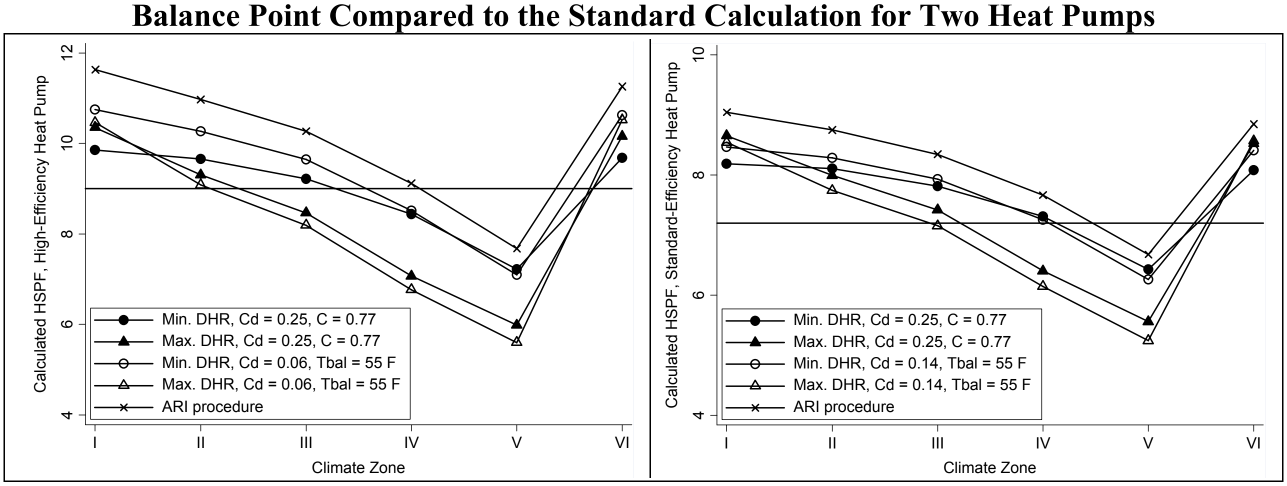
These graphs show that, for a given climate zone and building load, the differences are not great, with the largest about one rating point. For the minimum building load the use of a measured degradation coefficient and a balance point provides a higher HSPF than the use of a default degradation coefficient and the C-factor except in the coldest climate zones. For the maximum building load, the measured degradation coefficient and balance point produce a lower HSPF except in climate zone VI.

Figure 6. Effect on HSPF of Using Calculated vs. Manufacturer's Performance Data for Two Heat Pumps



Note: The horizontal line is the nominal HSPF.

Figure 7. Effect on HSPF of Using Both a Measured Degradation Coefficient and a Balance Point Compared to the Standard Calculation for Two Heat Pumps



Note: The horizontal line is the nominal HSPF.

However, all of the combinations result in lower HSPF calculations than those produced by the ARI procedure. This is because the credit for the improved degradation coefficient is taken without the penalty for using a house heating balance point rather than the C-factor. This suggests that the ARI procedure systematically overestimates the annual seasonal performance of heat pumps for homes that have a balance point of 55 F, in the range for new construction.

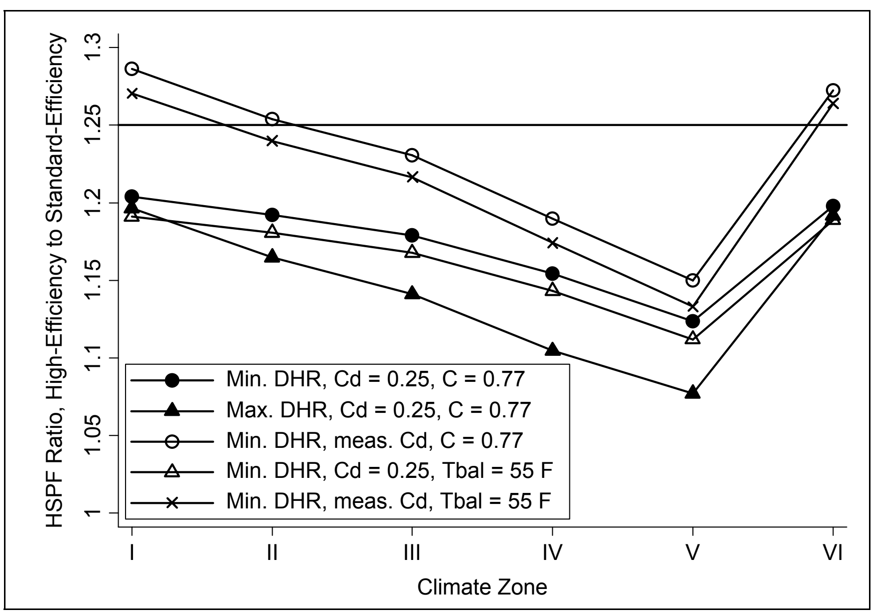
Percentage Improvement

Regardless of the extent to which various factors impact the HSPF, it is also of interest to determine whether an increase in the nominal HSPF translates into an actual improvement in energy usage by the same percentage. For example, the higher efficiency unit evaluated in this study has a nominal HSPF 25% greater than that of the standard efficiency model. If this 25% number holds up under a variety of conditions, then it could be said that a user at least knows the percentage improvement, even if the user does not know the actual energy usage.

Figure 8 shows the results of comparing the calculated HSPF values for the two heat pumps for several combinations of calculation methods. In this graph, the values are the calculated HSPF for the high efficiency unit under the conditions specified divided by the corresponding HSPF for the standard efficiency unit.

There are five conditions shown in Figure 8. The first two use the default degradation coefficient, the C-factor of 0.77, and the calculated performance data. The first of these two is the minimum building load and the other is the maximum building load. The other three cases all use some modification to the calculation procedure. The first uses the measured degradation coefficients appropriate for each unit; the second uses a 55 F balance point instead of the C-factor; and the third uses both the improved degradation coefficients and the 55 F balance point.

Figure 8. Improvement by Using the Higher Efficiency Unit Rather Than the Standard Efficiency Unit for a Variety of Inputs, expressed as a Ratio.



Note: The horizontal line is the nominal improvement of 25%.

There are very few cases where the percentage improvement is as much as the nominal 25%. Only cases using the measured degradation coefficient show that level of improvement, and only then in the mild climates. For the maximum building load, the apparent improvement drops below 10% for climate zone V. Without using the improved degradation coefficient, the apparent percentage improvement is usually below 20%, occasionally below 15%.

Some of the failure to reach the apparent 25% improvement may be due to the fact that the nominal HSPF of 7.2 for the standard-efficiency unit was not replicated. The higher HSPF for zone IV results in a reduced improvement. However, even if the nominal HSPF had been replicated, Figure 8 shows that the improvement is far from constant and that many climates may not realize the expected savings by using a higher efficiency unit.

Conclusions

The results of this study show that there are a number of factors that can have a significant impact on the seasonal performance of a heat pump, even without considering issues such as duct losses, control strategies, and sizing. The actual climatic conditions and the building load play a major role. Also, the replacement of certain aspects of the standard calculation procedure with more realistic methods can change the calculated values, often by 10% or more. Measured degradation coefficients increase the HSPF, and accounting for heat gains with a balance point instead of a C-factor that multiplies the load at every bin often reduces the HSPF. The combination of these two can either increase or decrease the HSPF, depending on the other parameters.

For current construction, which often results in homes that have balance points in the 50s, the standard calculation procedure appears to systematically overestimate the seasonal efficiency. This is because the rating is based on the measured degradation coefficient without being penalized for the effect that a low balance point has on the seasonal efficiency.

It is also not the case that a percentage improvement in the nominal HSPF corresponds to a realized energy use improvement. All of the factors that influence the actual HSPF also affect the percentage improvement, often resulting in a smaller improvement than would be assumed based on the nominal values. Therefore, programs such as HERS ratings that use this ratio to estimate the percentage reduction in energy use may often be overestimating the impact. For the Energy Star program, which requires a HERS rating of 86 (a 30% improvement), achieving this gain through increased heat pump efficiency alone may only result in an energy reduction on the order of 25% in many cases. This is especially the case in colder climates.

While it does not seem practical to stop applying HSPF values to heat pumps, it is important to understand the limitations of these values. They can indicate that one heat pump is more efficient than another, but to assess how much better for a particular application requires a more detailed calculation. For programs such as HERS ratings, data about the house and climate zone should be used to estimate an HSPF for each case.

The HSPF calculation procedure should be amended to account for gains using a balance point adjustment rather than a multiplier at each bin. In addition, publication of the degradation coefficients would enable people to more accurately perform the calculation for a specific case.

Given the sensitivity of the HSPF calculation to climatic conditions and building loads, it is also suggested that calculation results for all climates and for both minimum and maximum *DHR*s be provided with each unit. This should not represent an additional burden to the manufacturers, since they are already required to do the calculation for each of these cases. It would, however, provide significantly more information to users of the ratings, be they homeowners, program administrators, etc.

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