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Capacity Modulation Component Characterization and Design Tool Development*

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Objective

This effort has been focused on obtaining and evaluating modulating component and drive performance data for electric-driven, air-to-air residential heat pumps. The modulation means considered here are continuously variable-speed drives. The modulating performance data were obtained for purposes of:

- establishing a technology base for modulating components,
- providing a foundation for modulating model development, and
- screening compressor and drive types to be used in modulating system design assessments.

For the screening analyses, the relative performance of various compressors and drives was evaluated under appropriate modulating conditions. With the modulating components sufficiently characterized and the modulating models developed, the potential of advanced modulating heat pump systems for residential application can be assessed accurately.

Background

Preliminary capacity modulation assessment work was reported at the previous DOE/ORNL Heat Pump Conference.[1] In that work, annual performance gains of 36% (26.5% energy savings) compared to that of conventional single-speed heat pumps (with rather large cycling losses[a]) were predicted for a moderate climate. These predictions were based on early estimates of possible compressor and blower modulating-drive efficiencies, and they contained significant uncertainties with regard not only to drive efficiencies but also to basic hermetic reciprocating compressor performance over the assumed speed ranges. The dynamic losses for such modulating systems were likewise roughly estimated.

The need to better define modulating component performance led to the development, since the last conference,[1] of cooperative working arrangements between ORNL and manufacturers of modulating drives and compressors. From this industry cooperation, we have obtained performance data on:

- prototype permanent-magnet electrically commutated motor (PM-ECM) drives for compressor and blower applications,
- state-of-the-art inverter-driven induction motor (SOA IDIM) drives for compressor and blower application,
- reference sine-wave-driven induction motor (SWDIM) drives for first-generation and SOA modulating compressors,
- modulating reciprocating and scroll compressors driven by reference variable-frequency sine-wave power, and
- a modulating rotary compressor driven by a PM-ECM.

These data were augmented with modulating compressor and blower data taken by Miller[2] using first-generation IDIM and reference SWDIM drives in a continuously variable-speed heat pump (CVSHP).

Current Status

Modulating Drive Data

The preliminary ORNL modulating model[1] was modified to allow prediction of the compressor speed/torque requirements for heating and cooling mode operation.[3] With these speed/torque requirements established, operating efficiencies were evaluated for prototype PM-ECM, SOA IDIM, and reference SWDIM drives. These results were used in conjunction with the data taken by Miller[2] to obtain modulating drive (combined motor and inverter) efficiency comparisons over a range of technology levels.[3]

The resultant range of compressor drive efficiencies is shown in Fig. 1 for heating and cooling mode operation. Similar comparisons are shown in Fig. 2 for blower drives. Also shown in Figs. 1 and 2 are the initial assumed drive efficiencies of the preliminary ORNL analytical study[1] that were to have approximated advanced PM-ECM drive performance.

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[a] Equivalent cyclic degradation coefficients between 0.25 and 0.35 (including crankcase heater effect).

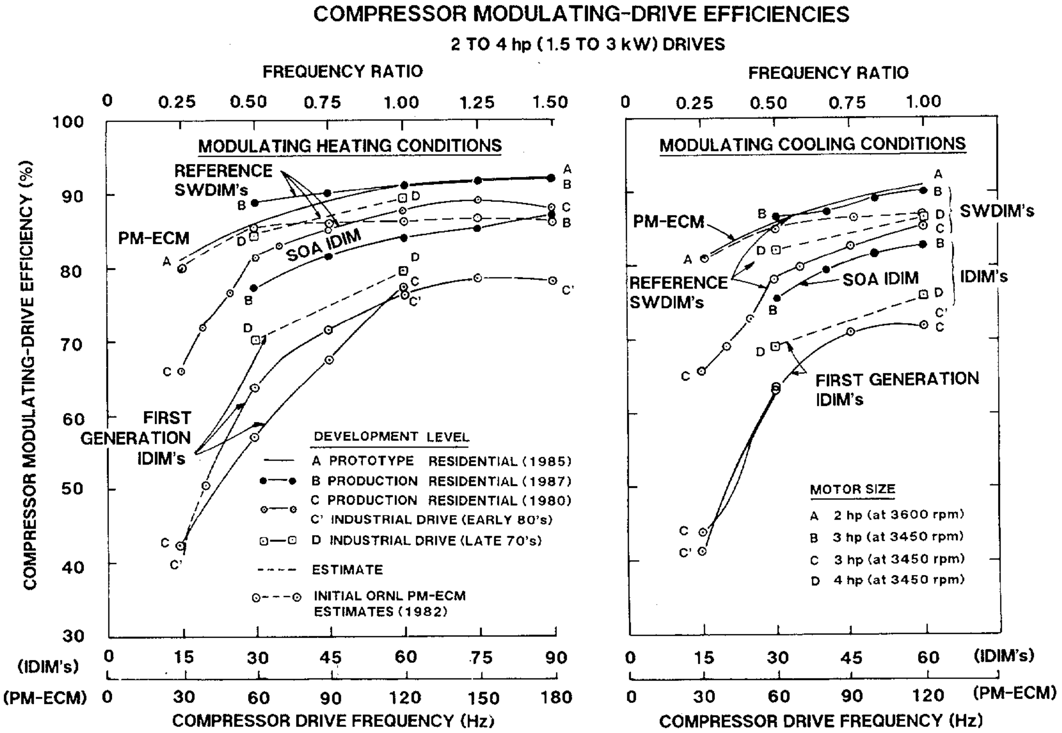

Fig. 1. Comparison of compressor modulating-drive system efficiencies vs frequency ratio / drive frequency for predicted modulating compressor load conditions.

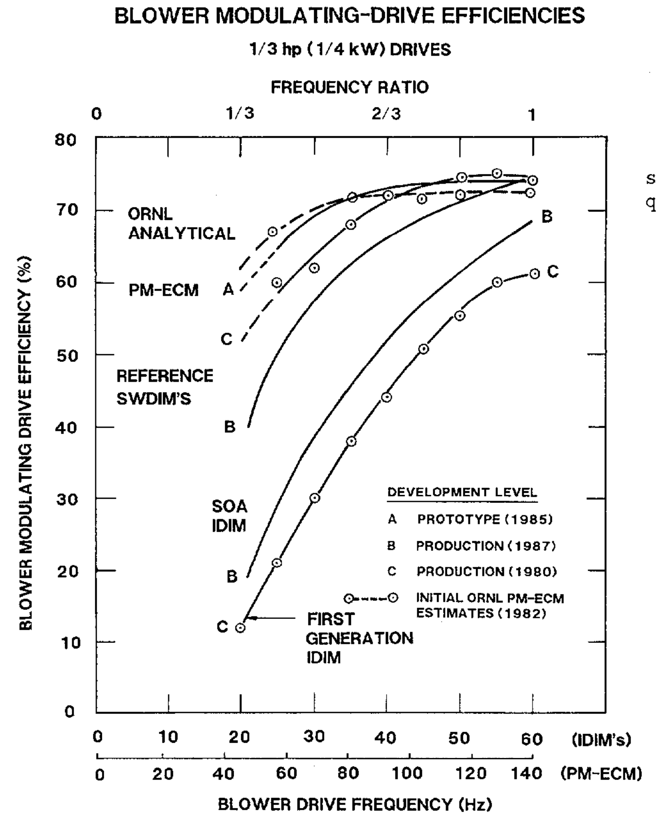

Fig. 2. Comparison of blower modulating-drive system efficiencies vs frequency ratio / drive frequency for typical modulating blower load conditions.

Modulating Compressor Data

Calorimeter data on hermetic reciprocating, rotary, and scroll compressors obtained from industry sources were reduced at ORNL to yield isentropic and volumetric efficiency values at discrete speeds as a function of saturation temperature and pressure ratio. From the preliminary modulating analysis,[1] predicted refrigerant conditions along the heating and cooling operating lines[3] were applied to the compressor efficiency data to obtain operating performance for speed ranges appropriate for each compressor.

These modulating results are shown in Figs. 3 and 4 where the isentropic and volumetric efficiencies, respectively, have been normalized to that of an SOA reciprocating compressor (compressor

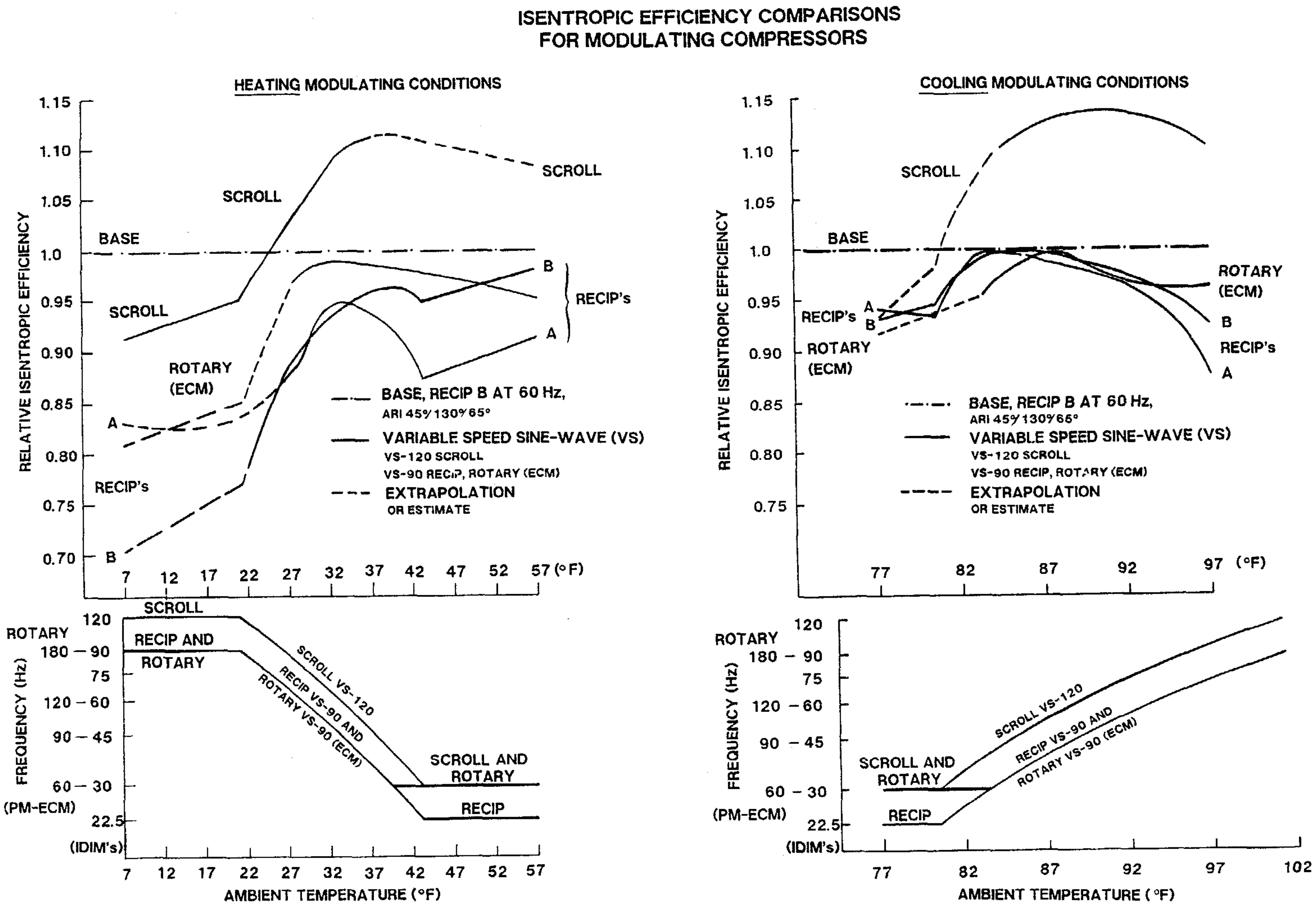

Fig. 3. Modulating compressor shell isentropic efficiency comparisons between sine-wave, frequency-modulated, scroll and reciprocating types (4 to 1 turndown ratios) and a PM-ECM modulated, rotary type (3 to 1 turndown ratio).

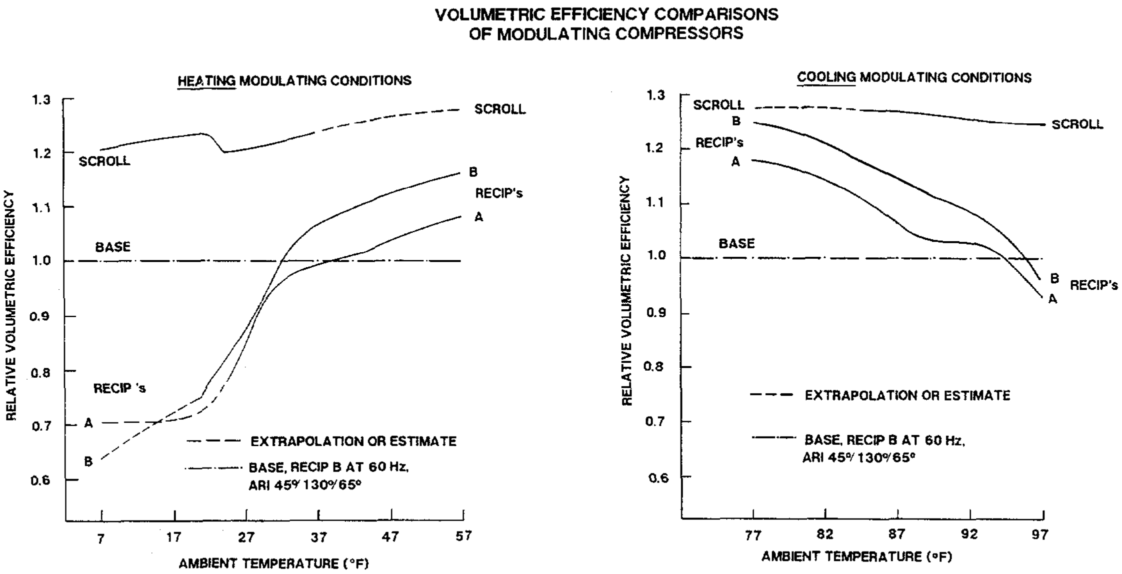

Fig. 4. Volumetric efficiency comparisons of modulating scroll and reciprocating compressors.

B operating at 60 Hz at the ARI cooling condition rating point[4]). In all cases, the compressors were driven by variable-frequency *sine-wave* power except for the rotary modulating case which was *PM-ECM* driven. Because all the compressors had approximately equivalent drive types, the differences in efficiency are mainly due to the specific compressor characteristics. Also shown in Fig. 3 are the frequency ranges used in the comparisons between compressor types.

In Fig. 5, comparable *single-speed* isentropic efficiency curves for the three types of compressors (at single-speed conditions but with three-phase motors) are added to those of Fig. 3. Also shown in Fig. 5, below the comparative efficiency curves, are the load-hour (load times hours) distributions for the assumed moderate climate (60% heating load) that were used to establish the heating and cooling operating lines.[1] These distributions can be used to determine the significance of the efficiency differences between compressors by noting the correspondence to the ambients where most heat pump output (load-hours) is required.

The results given in Figs. 3 and 4 were obtained from data sets that were each limited in some way (as noted by the dotted lines) as to the range of saturation temperatures and/or speed ranges over which the compressors were tested.[b] We are presently working to obtain more complete data sets -- both by further industry testing, where possible, and by complementary testing in our recently acquired modulating compressor calorimeter facility. Plans are to test additional selected modulating rotary, scroll, and possibly more reciprocating compressors, as they are available, over appropriate speed ranges and operating conditions. These tests will initially be with R-22 but will likely be expanded to alternative refrigerants or refrigerant mixtures as these become better identified.

Modulating Model Development

Curve fits to available calorimeter and application[2] data for reciprocating compressor A in Figs. 3-5 were used (as described by Miller[5]) in initial model validations against system laboratory data taken at ORNL[6] on a first-generation modulating heat pump. However, a more recent inspection of the triquadratic curve fits to the compressor data used there[5] indicated that some significant efficiency trends with speed were not being represented adequately. Through experience gained from different curve fitting attempts to more recently obtained reciprocating and scroll data, improved representations were achieved and implemented for, what we will call, the first level modulating heat pump design model (MHPDM). These representations generally will improve the absolute validation comparisons given by Miller[5] (especially in the heating mode, where initial underpredictions were mainly due to compressor data curve fitting errors).

This first level MHPDM requires the user to input compressor map-based coefficients for power and mass flow rate (or alternatively, for derived isentropic and volumetric efficiency) at each speed for which sufficient data are available.

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[b] Also, the scroll and reciprocating compressors shown in Figs. 3 and 4 have approximately 4 tons of cooling capacity at maximum speed compared to 2 tons for the rotary. The effects of downsizing the reciprocating and especially the scroll compressors by a factor of 1/2 on the relative compressor performances remain to be evaluated.

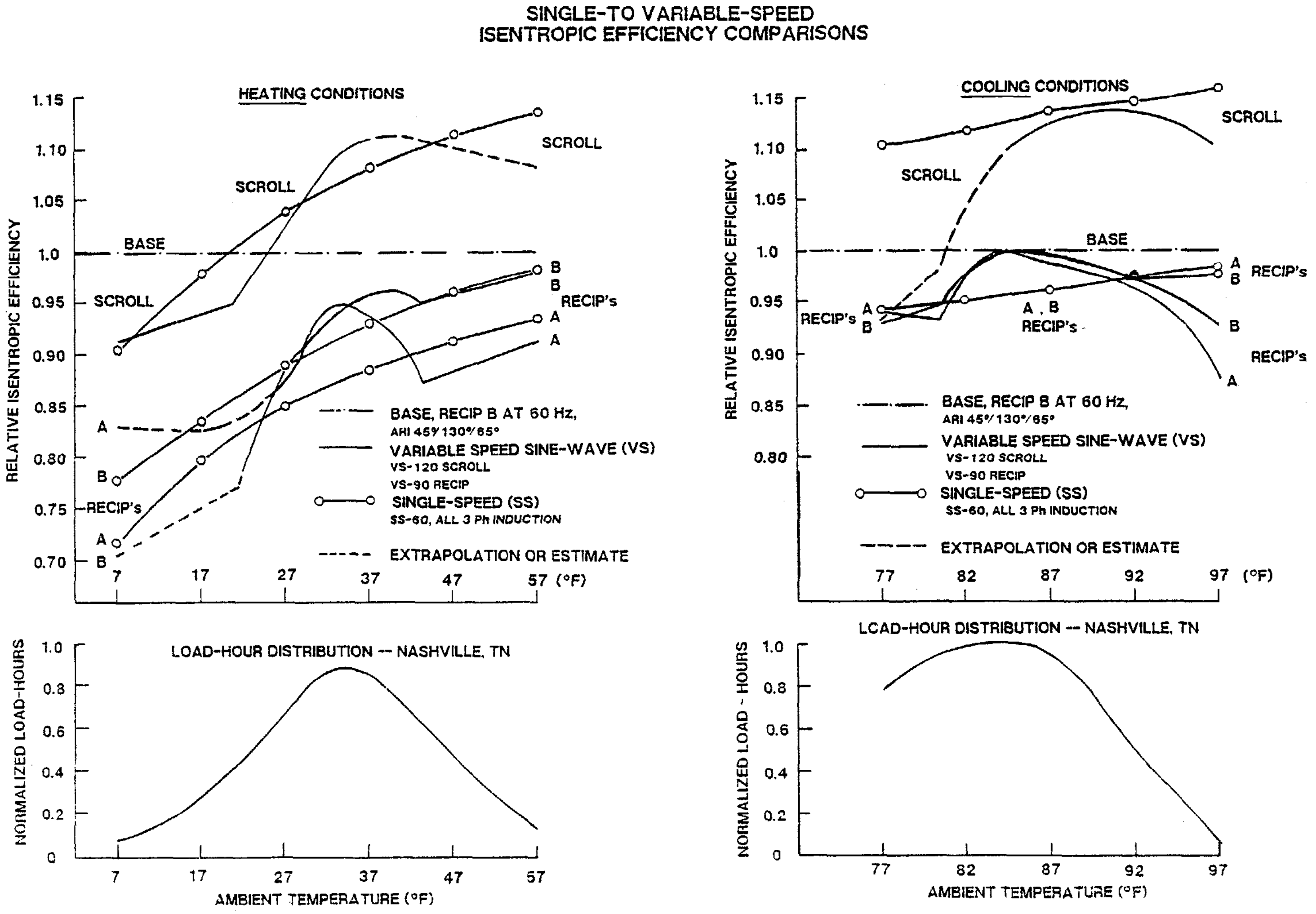

Fig. 5. Single(60 Hz)-to-variable speed compressor isentropic efficiency comparisons and corresponding load hour distributions for Nashville, Tenn.

In cases where minimal data are available, curve fits to the derived efficiency values have been found to give more reliable interpolations and extrapolations than similar representations based on basic power and mass flow data.

The supplied compressor data can be for an inverter-driven system, in which case the compressor map data are used directly, or for a reference SWDIM compressor. In the latter case, the user can have the program apply either first-generation or SOA inverter losses to the ideally driven (reference SWDIM) compressor. Alternatively, the user can use the SWDIM data directly to approximate performance with a PM-ECM compressor drive (as can be inferred from Fig. 1).

For the indoor blower and/or the outdoor fan, the user can select first-generation or SOA IDIMs or reference SWDIMs (again to approximate PM-ECMs as shown in Fig. 2).

In the second level modulating model (presently under development), the user will be able to replace the SWDIM compressor drive with a PM-ECM drive or another SWDIM drive (e.g., a more state-of-the-art modulating induction motor). This replacement option will allow the same basic modulating compressor characteristics to be applied with a different drive characteristic. In this way, calorimeter data on a given compressor can be generalized for significantly different drive combinations. We plan to use this version to more firmly establish the potential annual performance gains for ECM-driven reciprocating and scroll or rotary compressor combinations.

Modulating Design Tools

A key to the effective use of single-speed or modulating design models is a convenient yet flexible means to parametrically evaluate the effect of design, control, and operating variables. Such a "front-end" program is being made operational with the MHPDM for steady-state analysis with parametric evaluation of seasonal and annual performance to follow. The front-end program will allow use of the MHPDM and APF programs to parametrically generate sets of steady- state or seasonal performance data suitable for tabulation or for contour plotting with generally available PC contouring packages. Once these programs are sufficiently documented, they will be made available to the HVAC industry along with the second level modulating model.

A second generation Annual Performance Factor (APF)/Loads Model[7] to conduct seasonal performance analyses is presently operational but not yet fully documented. The second generation model includes the single-speed and variable-speed frosting and defrosting loss factors obtained by Miller[8,9] for a wavy fin outdoor heat exchanger with demand or timed[c] defrost operation. This version was used by Miller[5,9] to predict annual energy savings for modulating heat pumps based on laboratory measured steady-state and cycling performance improvements demonstrated at ORNL.[6,9]

Technical Accomplishments

The characterization and modeling work done since the last DOE/ORNL Heat Pump Conference[1] represents a logical complement to and progression from Miller's[5] laboratory and seasonal analysis of a first generation CVSHP with an ideally driven reciprocating compressor. In this project, data have been obtained and evaluated on advanced modulating drives capable of approaching (with SOA IDIMs) or exceeding (with PM-ECMs) the reference first-generation SWDIM performance obtained by Miller.[2] State-of-the-art and advanced compressors of three types have been characterized as to their relative modulating performance potential. Finally, a means of incorporating this data base into a modulating system model has been developed.

Summarized in this section are the more general results as well as some specific observations made in the course of the work on modulating component characterizations. The major features of the resultant first level MHPDM and related design tools are also described as are related applications to other projects. These data and programs provide the capability to look broadly yet accurately at important modulating system design issues.

Modulating Drives

Determined drive-efficiency characteristics for residential-sized compressors and blowers. These characteristics were shown in Figs. 1 and 2 for a range of technology levels (first-generation to SOA) at conditions representative of modulating system operation. The results indicate that advanced PM-ECM drives perform significantly better than first-generation and SOA IDIM drives.

Determined that PM-ECMs were the appropriate choice for advanced modulating system evaluation. Average reductions in seasonal component energy use with PM-ECMs in a moderate climate are summarized in Table 1. The energy savings are calculated for estimated average frequency ratios of operation for compressors and blowers. From this table and Figs. 1 and 2 the following conclusions can be made. *For a moderate climate*:

- PM-ECM compressor and blower drives offer average energy savings of more than 30 and 50%, respectively, over first-generation IDIM drives,[3]
- SOA IDIM drives can possibly provide up to two-thirds of the PM-ECM compressor energy savings but less than one-fourth of the ECM blower savings,[3]
- With first-generation modulating heat pumps, the drive inefficiencies take back essentially all of the 26.5% energy savings from heat exchanger unloading and from reductions in back-up heat and dynamic losses found in the preliminary ORNL modulation assessment.[1]
- PM-ECM drives perform at approximately the same level to better than ideally driven

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[c] Single-speed case only.

Table 1. Estimated average reductions in component energy use with PM-ECMs (moderate climate)

Component	Estimated average frequency ratio	PM-ECM energy use reductions from base IDIMs	
		1st Generation	SOA
Compressor			
Heating	1/2	30%	10%
Cooling	1/3	25%	12%
Blower	1/2	57%	45%

(reference SWDIM), high-efficiency, three-phase induction motors and better than single-speed, single-phase induction motors (<85% efficient). On the basis of drive efficiency alone, PM-ECM-driven modulating systems would have an advantage in lowering peak cooling demand compared to single-speed (single-phase) systems.

Furthermore, from discussions of reliability and cost issues of PM-ECMs with manufacturers of both PM-ECM and IDIM drives, we concluded that ECM-driven compressors were an appropriate choice for use in the evaluation of advanced modulating systems.[3]

Identified modulating motor/drive design requirements. Through an analysis of compressor and blower torque loadings (as a function of speed) weighted by operating hours, we found[3] that:

- compressor drives should be designed for peak efficiency at or just below full load compressor torque and
- blower drives need performance maximized near 25% of full load compressor torque.

From this work, we also determined that compressor motors required to run 50% above nominal speed in cooling will require a motor twice as strong as if the motor is only required to be oversped at low ambients in the heating mode.

Modulating Compressors

Developed a set of representative operating conditions for modulating compressors. Starting from an optimized variable speed design,[1] we obtained contour plots of heat exchanger saturation temperatures and pressure ratio as functions of compressor frequency ratio and ambient temperature.[3] These plots were generated for both heating and cooling mode operation over reasonably wide speed ranges. As such, the contour plots serve as generalized mappings of approximate modulating compressor conditions ranging from fully loaded (high flow) to unloaded (low flow) heat exchanger operation.

Using these condition maps, we found that modulating compressors would experience the most operating hours at pressure ratios (P_r) near 2.0 in cooling mode and 3.0 in heating as compared to 2.6 and 4.0, respectively, for a comparable single-speed compressor. These results indicate that compressors for modulating heat pumps should be designed for best isentropic efficiency at pressure ratios around 2.5 (the average of the ratios over both modes) as compared to an average pressure ratio of 3.3 for the conventional single-speed application.

Conducted initial modulating compressor screening and quantified potential modulation advantages of scroll vs reciprocating compressors. From the compressor screening analysis, comparative modulating performance of three compressor types was obtained, as shown earlier in Figs. 3 and 4. In Fig. 3, the scroll compressor (overall) isentropic efficiencies are seen generally to exceed those of the reciprocating and ECM-rotary compressors by 10 to 15%. An exception to this occurs at the lowest speed, mild ambient cooling conditions, where the relative efficiencies are nearly equivalent.

With regard to volumetric efficiency comparisons, in Fig. 4 the reciprocating compressor trends (of increasing volumetric efficiencies at milder ambients) are seen to be opposite to modulating needs in both heating and cooling modes. In contrast, the volumetric trends for the scroll compressor were close to neutral. This volumetric advantage for scroll compressors (and to a similar extent for rotaries) will allow either a wider modulation capability over a given frequency range or will require less of a drive frequency range for the same modulation capability (e.g., approximately a 3:1 frequency ratio for a scroll compared to 4:1 for reciprocating).

Determined that modulating compressors have isentropic efficiencies approximately equivalent to those of single-speed compressors under their respective application conditions. This result is observed in Fig. 5 where isentropic efficiencies are compared for single and variable speed compressors (both with the same three-phase motors).

In general, the variable-speed compressors have efficiency advantages up to 5% (over the single-speed) for the ambient temperatures about which the required heat pump heating and cooling outputs (load-hour distributions in Fig. 5) are a maximum. At the milder and more severe ambients, the situation is reversed with the single-speed compressors having a slight advantage.

The major exception to this rough equivalence is for the scroll-to-scroll comparisons at low speed, mild ambient cooling conditions. Here the variable-speed scroll performance is 10 to 15% below that for a single- speed scroll. However, as will be shown in the next section, the heat exchanger unloading advantage of the modulating system at these conditions will more than offset the compressor efficiency loss. Even so, improved scroll compressor design for these mild ambient, low pressure ratio conditions (P_r less than 2.0) would further boost the modulating compressor isentropic efficiency at the low-speed cooling rating conditions (of 67 and 82°F). The use of by-pass ports to improve low-pressure ratio performance has been recently reported by the Japanese.[10]

Determined that the peak cooling demand of modulating systems can be equivalent to or lower than that of single-speed systems. At the maximum cooling design conditions (95°F for Nashville, Tenn.), the variable-speed compressors show about a 5% isentropic efficiency penalty compared to single-speed (Fig. 5). This efficiency penalty occurs because the variable speed design has fewer heat exchanger circuits (and thus a greater coil pressure drop at these conditions) in order to boost the per circuit flow rates at low speed operation. The 5% efficiency penalty is for the same drive type between the single- and variable-speed compressors.

A modulating compressor *with an advanced ECM drive* (having a 4 to 5% efficiency advantage over a single-speed motor) would therefore yield an overall peak cooling demand *equivalent* to that of a single-speed compressor. The use of ECM *blower* drives would result in a *lower* overall system demand compared to that of a single-speed system. Futhermore, the circuiting on the variable-speed system could be made more equivalent to the single-speed system if reducing peak demand were a higher priority than maximizing low speed performance.

From the above observations on modulating drive and compressor performance compared to single-speed components, the following can be concluded. For modulating applications, *heat exchanger unloading changes* from different compressor speed / frequency range capabilities, different compressor volumetrics, and various flow control options *will be as or more important than differences in compressor isentropic efficiency*. Therefore, issues in both these areas need to be considered in advanced modulating system assessment.

Modulating Component Models

Completed first level speed-modulated compressor models. These models can be used to predict compressor performance with first-generation or SOA IDIM systems or for reference SWDIM cases (approximating PM-ECMs). The modulating compressor models are based on:

- inverter losses derived from ORNL tests of a first generation CVSHP,[3,2] and SOA IDIM loss data obtained from industry bench tests,[3] and
- modulating sine-wave-driven compressor data from manufacturers.[3]

The user also has the option to directly provide curve fits for inverter-driven compressor data.

Completed first level modulating indoor blower and outdoor fan models. Models can be used to similarly predict modulating blower or fan efficiency with first-generation or SOA IDIM drives or for a reference SWDIM case (approximating a PM-ECM). The blower models are based on:

- first-generation IDIM and SWDIM blower drive efficiency data obtained from ORNL tests of a CVSHP,[3] and
- SOA IDIM and SWDIM efficiency data obtained from a manufacturer.[3]

Completed first level charge inventory model to allow prediction of charge effects in modulating systems and to accommodate advanced modulating flow control devices (by fixing refrigerant charge and determining required condenser subcooling or evaporator superheat levels). The charge inventory model includes:

- user choice of inventory methods ranging from simplified to SOA,[11] (We determined that a simplified analytical formulation was sufficient for early design work and much faster than more accurate methods requiring numerical integration.[11])
- tabulations of steady-state on- and off-cycle charge distributions, and
- a j-tube accumulator model adapted from NBS mixed-refrigerant heat pump simulation.[12]

Completed major update of air-side heat transfer and pressure drop calculations for improved prediction *for modulating air flows* based on work by Gray and Webb.[13] Other heat exchanger modeling improvements included improved augmentation factors dependent on Reynolds number and fin pattern specifics. These were:

- much improved wavy fin correlations obtained from DOE/ORNL supported work at the Westinghouse R & D Center[14] and
- expanded louvered (strip) fin correlations.[15]

Modulating Applications, Validations, and Design Tools

Assisted in the application of ORNL Heat Pump Design Model to variable-speed engine-driven heat pump simulations. Through a Work-for-Others contract, ORNL adapted the Mark III ORNL Heat Pump Design Model (single-speed) *to a variable-speed* (1000 to 3000 rpm) Stirling-engine-driven heat pump application.[16] This adaptation was accomplished using proprietary Borg-Warner / Stirling Power Systems (SPS) engine, compressor, and radiator representations for a 10-ton commercial system. The modified model was transferred to Borg Warner for their use in system design and control analysis for the Gas Research Institute (GRI).[17]

We also provided the Mark III ORNL Heat Pump Design Model[6] and Mark I APF/Loads Model on an advance basis to Battelle Columbus Laboratory. These programs were selected[18] and modified by Battelle to model residential internal-combustion, engine-driven gas-fired heat pumps[19] for another GRI development project. The Battelle project was also a variable-speed application (again 1000 to 3000 rpm).

Completed first level electric-driven ORNL MHPDM including charge inventory capability. This involved integrating the developed modulating component models into the existing ORNL single-speed design model.[6] Program input requirements were modified with an emphasis on minimizing changes required to existing heat pump model data sets to convert to the newer model.

Conducted validation of initial ORNL MHPDM using ORNL breadboard variable-speed system data.[5,6] Results indicated that best model agreement was obtained at the lower speeds, while some performance overpredictions occurred at higher speeds because of limitations of the simplified circuiting models with higher subcooled (or superheated), more heavily loaded heat exchanger conditions.

Additional validations of the original single-speed version in nonmodulating and modulating applications have been reported as satisfactory to excellent by Fischer,[20] Westinghouse (dual stroke application),[21] Battelle Columbus,[18] and Borg-Warner.[17]

Developed framework for integrating the ORNL Steady-State and APF Design Models into a design package for generating parametric performance data (suitable for contour plotting). Performance data parametric options include:

- choice of at least 25 design, control, and operating variables,
- steady-state performance results for fixed ambients or range of ambients, and
- seasonal or annual results for various operating or sizing strategies.

Potential Benefits from Capacity Modulation

Estimates of Steady-State Benefits

The net compressor efficiency changes and heat exchanger unloading benefits from modulation can be related directly to system EER gains. Provided the fan power is roughly a constant fraction of the compressor power, the *modulating* (vs) *system* EER gains (steady-state) compared to a single-speed (ss) system are given approximately, at each ambient temperature, by

$$\frac{\text{System EER}_{vs}}{\text{System EER}_{ss}} = \frac{\eta_{is,vs}}{\eta_{is,ss}} \bullet \frac{\text{EER}_{hx,vs}}{\text{EER}_{hx,ss}} \qquad (1)$$

$$= \begin{array}{c}\text{compressor}\\\text{efficiency}\\\text{effect}\end{array} \bullet \begin{array}{c}\text{heat exchanger,}\\\text{unloading}\\\text{effect}\end{array}$$

where η_{is} represents compressor shell overall isentropic efficiency (including inverter drive losses) and EER_{hx} is the ideal compressor EER based on heat exchanger saturation conditions.

In Eq. (1), the compressor efficiency effect can be obtained from comparisons given in Fig. 5 between single- and variable-speed compressors (assuming the same motor type). Adjustments for modulating drive differences from reference SWDIM values can be obtained from Fig. 1.

The second factor in Eq. (1), *the heat exchanger unloading effect, is the dominant steady-state modulation benefit. This effect is determined by the compressor effective modulating range* (from both speed range and volumetric efficiency factors) *and by the refrigerant flow control design.* The resultant reduction in modulating system pressure ratio from these factors determines the heat exchanger unloading gain.[d] In first-generation designs, the primary question was whether losses in the modulating drive and compressor combination at the lower speeds would offset the obtained heat exchanger unloading benefits.

Examples of heat exchanger unloading effects are given in Fig. 6 for heating and cooling mode operation. The examples are based on the same compressor operating conditions[3] used in the compressor screening shown in Figs. 3-5. Refrigerant control strategies approximately optimal for single- and variable-speed cases were assumed to calculate the ideal heat exchanger (compressor) EER ratios. The reference for each ambient was the computed $\text{EER}_{hx,ss}$ based on heat exchanger conditions under single-speed operation.

In Fig. 6, *the heat exchanger unloading benefits* are seen to *give large system EER gains* at the *lower speed, milder ambient conditions* in either mode. For example, with a 4:1 modulation ratio, *a steady-state gain of 55% is indicated at an 82°F ambient in cooling mode, with a 46% gain*

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[d] Eq. (1) can also be applied to modulating-to-modulating system comparisons. In this case, the single-speed terms in Eq. (1) would be replaced by the base modulating system. Here the heat exchanger unloading effect will cancel out if both systems have the same effective modulation ratios.

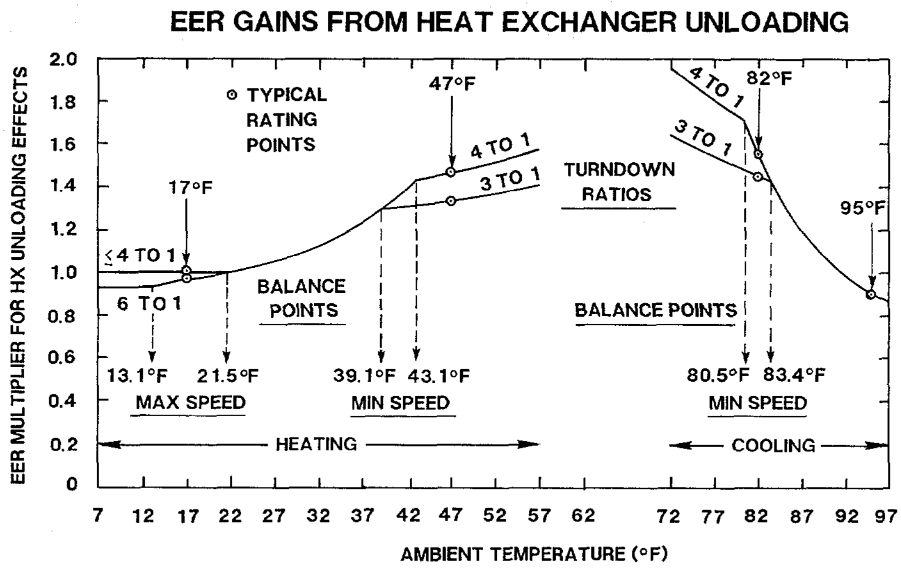

Fig. 6. Examples of steady-state EER multipliers for heat exchanger unloading effects for various turndown ratios in heating and cooling modes.

seen at 47°F heating. The reduction in heat exchanger unloading benefit from a smaller modulation range can also be seen from Fig. 6. In conjunction with Figs.1 and 5, Fig. 6 can be used to predict approximately the system EER (steady-state) gain from modulation at any selected ambient for the available compressors and speed ranges.

From this discussion, it can be seen that, to evaluate the steady-state benefits of modulating systems,[e] the unloading effects and the resultant compressor isentropic efficiencies must be considered together. Heat exchanger unloading is a rather involved interplay of compressor and blower speed ranges, compressor volumetrics, and system control strategies. The simplified relational analysis presented in Eq. (1) illustrates the need for optimal modulating system design and control to fully realize the performance potential of such systems. The design tools currently being developed and demonstrated are intended to assist the HVAC industry with this task.

Estimates of Annual Benefits

To evaluate the benefits of advanced modulating systems in terms of annual performance gains, we must add to the above considerations the effects of cycling, frosting/defrosting, and back-up heat reductions. At present, our best basis for overall savings estimates are the results of our initial analytically[1] and experimentally[6] optimized designs as evaluated on an annual basis with the ORNL APF/Loads Model.[1,5] Because the efficiency of the first-generation SWDIM drive (SWDIM curve C in Fig. 1) tested by Miller[6] is lower than that of the prototype ECM drive performance (also in Fig. 1), we would estimate higher possible annual performance gains than those given by Miller.[5]

For a PM-ECM-driven, reciprocating compressor system, we now estimate *annual performance gains for Nashville, Tenn.* (with 60% heating load) *of 30 to 35%* (23 to 26% energy savings) as compared to those of an optimally designed, single-speed system with comparatively reduced cycling loss factors.[5] *For a PM-ECM-driven scroll system,* the compressor efficiency comparisons shown in Figs. 3 and 4 suggest that the *annual performance gains, compared to an optimally designed single-speed reciprocating system, could be 45 to 50%* (31 to 33% energy savings). A major part of our analysis work in the near future will be to firmly establish benchmark efficiency improvement levels that can be expected on a nationwide basis for these two PM-ECM-driven systems.

Future Work

Ongoing and planned work is directed toward areas intended to assist industry in developing modulating systems capable of approaching these performance potentials.[f] Benefits from work to be accomplished in the near future include:

- establishment of a broader technical performance base of drive and compressor efficiencies for use in modeling modulating components and in providing perspective on progress made in modulating component performance,

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[e] Compared to either single-speed systems or to other modulating systems.

[f] Within the constraints of general energy economics and specific economic criteria established by each company.

- transfer of design programs to the HVAC industry for development and improvement of future generation modulating heat pumps, and

- evaluation of near- and longer-term benchmarks of potential modulating heat pump performance (i.e.,

  - near-term, PM-ECM / reciprocating compressor-based and

  - longer-term, PM-ECM / scroll or rotary compressor-based)

  through the identification of general sizing, component configuration, and control characteristics for best modulating system efficiency in different climates.

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