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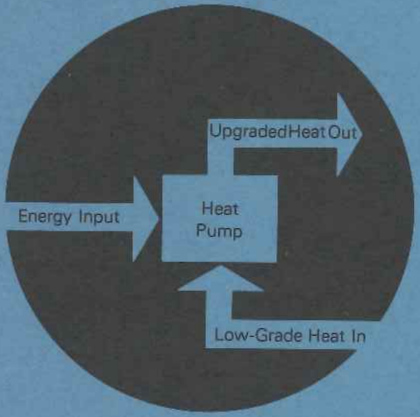

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COMPUTER AIDED HEAT PUMP DESIGN AND OPTIMIZATION*

OAK RIDGE NATIONAL LABORATORY
CONTRACT NUMBER W-7405-eng-26
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OBJECTIVE

The objectives of this project are to develop and demonstrate analytical methods to predict the performance of existing and proposed heat pumps; to develop and demonstrate computer programs to serve as tools for the design and optimization of high efficiency heat pumps.

BACKGROUND

The MIT heat pump model (1) served as a starting point in the development of analytical methods for heat pumps at ORNL. The MIT program was modified for our use and documented (2, 3) as a preliminary version of the ORNL heat pump model. An improved version of the program was made available to other users in 1979. Copies of the computer program have since been sent to about 30 requestors for use on their computers. Our own use of the program in our optimization studies as well as the experience of other users has revealed the need for additional capabilities in the model. New capabilities were added to the program during the past year, using correlations from the literature, when they were available, or correlations developed at ORNL. These additions have improved the model significantly and extended its applicability. The result is a second generation of the computerized model, one that can be used by engineers who are not necessarily computer experts.

At ORNL, the heat pump model was used in an attempt to predict the increased heat pump efficiency that could be expected from the use of improved components, and to explore the practical limits of efficiency. It soon became obvious that a systematic approach is required to obtain consistent and credible results. The heat pump model was connected to an optimizing program; the combined programs were used to vary, simultaneously and independently, selected design parameters in such a way as to maximize the predicted heat pump efficiency, and thus assure maximum benefit from improved components.

SUMMARY

A computer model of electric-motor-driven heat pumps was developed to provide detailed analyses of the performance of existing or proposed heat pumps. To the extent possible, the model is based on the physical principles underlying the processes and on basic correlations, with minimal use of empirical correlations. This approach was adopted so as to give the model maximum flexibility; to allow its use for analyzing design concepts that depart from current practice. The computer program is organized to facilitate its use by engineers who want to concentrate on a heat pump design, not a computer program.

The heat pump model was connected to an optimization program in order to maximize the predicted heating efficiency by simultaneously varying ten design parameters to find the combination giving the highest COP at a specified heating capacity. The program we used is based on the steepest ascent algorithm with refinements which allowed us to specify a minimally acceptable supply air temperature and an upper limit on the total heat exchanger area, as well as holding the heating capacity constant. We used this combined code to find the designs with the highest COPs for a series of system improvements: increasing compressor efficiencies, fan efficiencies, and total heat exchanger area.

We used the specifications for a heat pump tested in our laboratory (i.e., heat exchanger descriptions, air flow rates, compressor displacement, etc.) as input data for a base case system for validation and comparison purposes. When ten design variables were optimized for this system, there was a 21% improvement in predicted heating efficiency. Assumed increases of 17% and 34% in overall compressor efficiency (from 47% to 55% and 63%) led to 11% and 22% additional improvements in maximum predicted COP, respectively. It is noteworthy that the optimum system with the 63% compressor efficiency had a total displacement 20% smaller than our base case with a required shaft power of 2.24 kw (3.0 hp) rather than 3.36 (4.5 hp).

This analysis showed us the optimal designs and some trends from one level of improvement to the next. It did not, however, give us any indication of the sensitivity of efficiency to variations from the optimal design. We used the heat pump model to do parametric studies to show the flexibility or latitude that exists about the optimum for selecting system components. This analysis is displayed graphically as plots of contours of COP for wide ranges of design variables, two at a time, about their optimal values.

TECHNICAL ACCOMPLISHMENTS

Developed a practical, validated design tool for heat pumps and air conditioners. The heat pump computer model was significantly improved from the program reported in 1978 (2). New capabilities were added, engineering methods and correlations were improved, and the program was made significantly easier to use.

It requires as inputs:

- geometric description of the heat exchangers and interconnecting pipes;
- a specification of the flow control device (or as an option, the desired condenser subcooling);
- the desired suction line superheat;
- the air temperatures at the entries to the heat exchangers;
- estimates of the condensing and evaporating temperatures and refrigerant mass flow rate (to get the calculations started); and
- data for either the efficiency and loss or map-based compressor model.

The model can be used to calculate:

- heating and cooling capacity, latent and sensible, and COP;

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- compressor and fan motor power consumptions;
- refrigerant temperatures and pressures throughout the circuit and the mass flow rate;
- air-side temperature, pressure, and humidity changes; and
- compressor efficiency and heat exchanger effectiveness at the conditions specified.

The user has the option to specify:

- a map-based or an efficiency and loss compressor submodel;
- draw through or blow through fans;
- motor efficiency curves;
- any of eleven refrigerants;
- correlations for smooth or wavy fins; and
- thermostatic expansion valve (TXV), capillary tube, or fixed condenser subcooling to control refrigerant flow (in the latter case the TXV and capillary tube parameters necessary to achieve the desired level of subcooling are computed and printed).

The model is being validated against data collected in our laboratory and is being documented. It will be available for distribution this summer when these two tasks are completed.

Developed and demonstrated a technique for heat pump design optimization. We demonstrated the use of heat pump design techniques to find the system configuration with the highest predicted efficiency while satisfying constraints due to engineering considerations, and those chosen to limit component costs or sizes. This method allows engineers to design systems which obtain the maximum possible benefit from each improvement in individual components. We have plotted steady-state heating COP (at the ARI high temperature rating point) in Figure 1 against a normalized scale for total heat exchanger area. A unit which was studied in our laboratory (4) has been used as a base case and arbitrarily assigned a relative heat exchanger area of 1.0. Several points and three curves representing improved systems have been plotted with respect to the base case and labelled with their overall compressor efficiencies. Two of the individual points are commercially available, state-of-the-art heat pump systems and one is the predicted maximum COP attainable by our base case heat pump, if the system were optimized. The nine points that were used to draw the three curves were obtained by substituting high efficiency fans for those in our base case unit and optimizing the configurations for three levels of heat exchanger area and three compressor efficiencies. Figure 1 shows an increase in predicted COP for our base case from 2.4 (labeled with a 1) to a maximum of 2.9 (labeled with a 2) by finding the optimum combination of the design variables, but without increasing any component efficiencies or total heat exchanger area or decreasing heating capacity. This figure also shows the fairly uniform increases in predicted COP resulting from 17% to 34% improvements in overall compressor efficiency (from 47% to 55% and 63%, respectively). Another conclusion that can be drawn from the figure is the decreasing improvement in system operation resulting from increasing levels of total heat exchanger area. Doubling the total heat exchanger area yields an increase of 15% in predicted COP over the optimum configurations with smaller condensers and evaporators for all three levels of compressor efficiency. The relative heat exchanger area, however, must be quadrupled to give a 30% increase in COP.

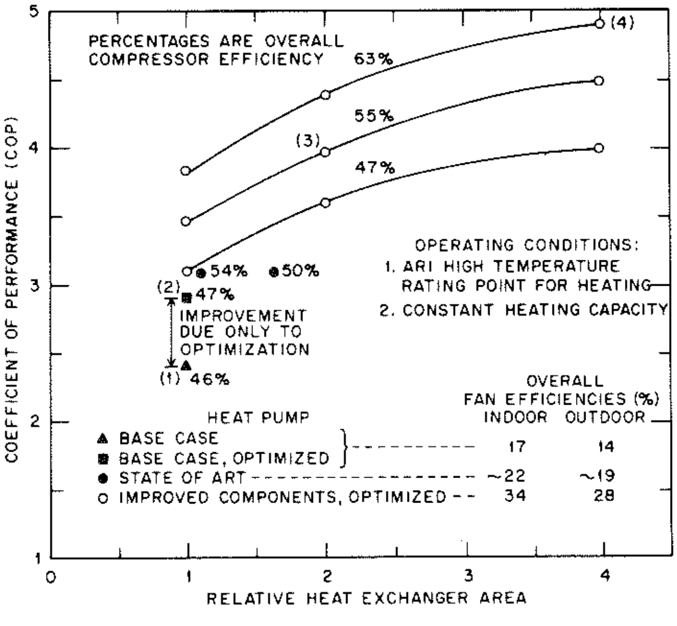

Fig. 1 Effects of compressor efficiency, heat exchanger area, and design optimization on heat pump COP.

Devised a technique for evaluating design tradeoffs. We demonstrated a means of displaying design flexibility by using the heat pump model to plot lines of constant COP and capacity over wide ranges of design variables. Figure 2 shows how the predicted COP and capacity change as the condenser and evaporator air flow rates vary about the values found by the optimization program. As may be seen from the figure, condenser air flow rate may be varied from about 1300 to 1900 cfm, providing the evaporator air flow rate is correspondingly adjusted, without changing the capacity more than 2% or reducing the COP more than 1.5%. Plots of this nature

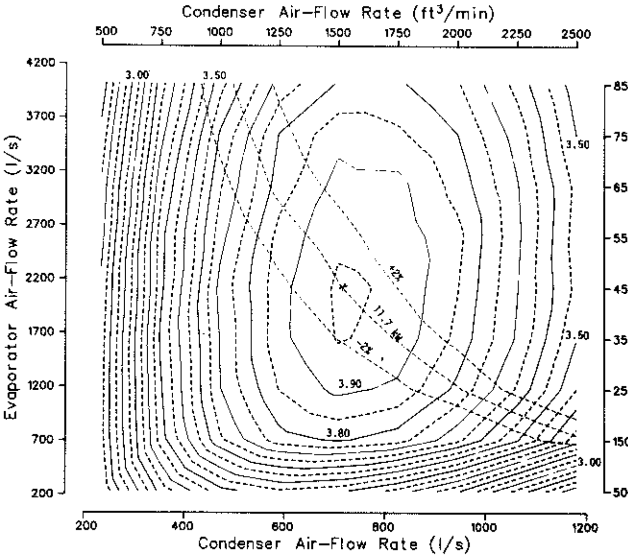

Fig. 2 Sensitivity of COP and heating capacity to air-flow rates at 47 F.

can be used to analyze the sensitivity of COP to variations about the optimum design and how design parameters can be adjusted simultaneously to maintain high efficiency and desired capacity.

Showed that optimum design is more important in high performance heat pumps. We found that good system design becomes much more critical as system efficiency increases. Figure 3 shows how the maximum predicted COP varies as the total compressor displacement changes for several levels of system improvements. The lowest curve was produced by holding the geometry of the heat exchangers fixed at our base case design while the COP was maximized for each of several compressor displacement values by finding the optimum air flow rates and condenser subcooling (the heating capacity was held constant). The other curves are all the results of finding the maximum COPs after optimizing the heat exchangers and adding additional levels of system improvement. It is noteworthy that the predicted COP is substantially increased from the base case and the compressor size reduced by 20% while the heat pump capacity remains constant. (Though it is not shown on these curves, the required motor shaft power is also reduced — from 3.36 (4.5 hp) to 2.24 kw (3.0 hp) — and thus, a smaller motor is acceptable). The most important point, however, is that as each successive component improvement is made, the system efficiency curve has a sharper peak and the proper sizing of the compressor is increasingly important. Similar analysis could be done with any of the design parameters on the horizontal axis.

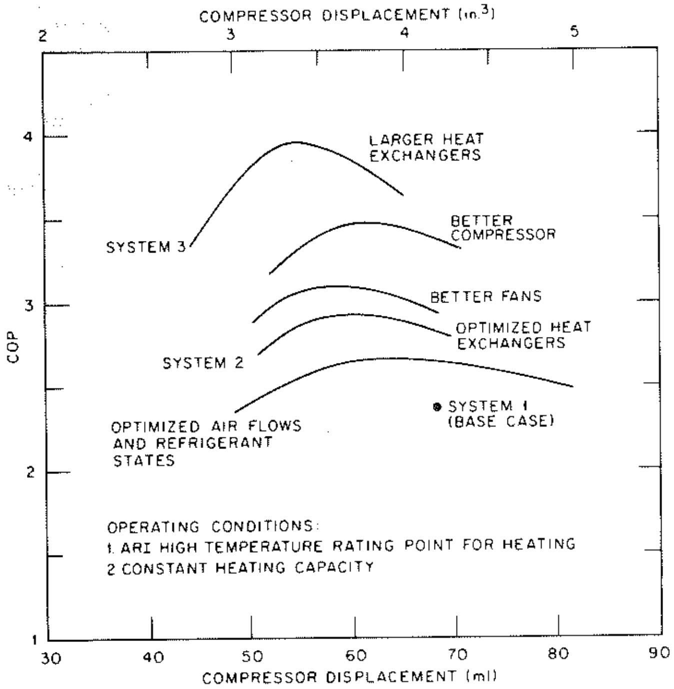

Fig. 3 COP vs compressor displacement for a series of successive system improvements.

FUTURE ACTIVITIES

Contract activities. The ORNL Heat Pump Design Model will be maintained. Minor changes to the program will be considered if the demand for new capabilities is strong and as new engineering methods and correlations become available.

It is anticipated that the optimizing technique will be applied to single-speed heat pumps for both heating and cooling performance and to capacity modulating systems. Methods will be developed to optimize performance for best seasonal performance instead of steady-state efficiency. Heat pump designs that produce maximum efficiency and are cost-competitive will be sought.

Post-contract activities. Not applicable.

REFERENCES

1. C. C. Hiller and L. R. Glicksman, Improving Heat Pump Performance via Compressor Capacity Control-Analysis and Test, Report No. 24525.96, Heat Transfer Laboratory, Massachusetts Institute of Technology (1976).

2. R. D. Ellison and F. A. Creswick, A Computer Simulation of Steady-State Performance of Air-to-Air Heat Pumps, ORNL/CON-16 (March 1978).

3. R. D. Ellison, et al., "Heat Pump Modeling: A Progress Report," Proceedings of the Fourth Annual Heat Pump Technology Conference, Oklahoma State University, Stillwater, Oklahoma, April 9-10, 1979.

4. A. A. Domingorena, Performance Evaluation of a Low-First-Cost, Three-Ton, Air-to-Air Heat Pump in the Heating Mode, ORNL/CON-17 (October 1978).

PUBLICATIONS

1. C. K. Rice, S. K. Fischer, et al., "Design Optimization of Conventional Heat Pumps: Application to Steady-State Heating Efficiency," ASHRAE Transactions 1981, Vol. 87, Pt. 1.

2. C. K. Rice, S. K. Fischer, et al., Design Optimization and the Limits of Steady-State Heating Efficiency for Conventional Single-Speed Air-Source Heat Pumps, ORNL/CON-63, in preparation.

3. S. K. Fischer and C. K. Rice, Heat Pump Design and Simulation Model (working title), in preparation.