I E A - INTERNATIONAL ENERGY AGENCY

Implementing Agreement on Advanced Heat Pumps

ANNEX XII

"Modelling Techniques for Simulation and Design of Compression Heat Pumps"

Annex XII Final Report

by

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CONTENTS

INTRODUCTION

Annex XII "Modelling Techniques for Simulation and Design of Compression Heat Pumps" was established as a working group to evaluate the state of the art of computer modelling of elettrically driven heat pumps with ambient air as heat source, in the participating countries.

Annex XII had to last 18 months, with the possibility of an extension requested by two or more participants acting in the Executive Committee.

Austria, Belgium, the Federal Republic of Germany, Italy, Japan and the United States participated in the Annex; the United States acted as Operating Agent.

At the end of 1988 a final report was prepared by Mr. S. Fischer from the US Oak Ridge National Laboratory summarizing the contributions of the participants to the Annex.

This report can be now considered as an interim report and is included in this final report as attachment 1.

A report from Italy, not included in the interim report, was prepared on April, 1989 and distributed to all the participants in the annex on June 1989 during the working meeting held in Brugge. The report regarded the validation of ORNL Heat Pump Design Model MARK III by means of experimental tests carried out on an air-to-air heat pump prototype designed by using this model.

In the same working meeting Italy proposed an extension of the Annex XII validity duration and the proposal was approved by the Executive Committee on June 22, 1989.

The working program was focused on variable speed heat pump systems.

The approved extension of the working program is in attachment 2. Five countries having ongoing national programs in the field of variable speed systems, agreed to participate in this second phase of the Annex: Austria, the Federal Republic of Germany, Italy, Switzerland and the USA.

Italy, represented by Tecnars, accepted to act as Operating Agent during the extension period of the Annex XII.

Although the conclusion of the activities was scheduled for the spring 1990, some unexpected events, mainly due to difficulties in acquiring variable speed compressors for laboratory tests, caused a considerable delay, so that only at the end of 1991 all activities were concluded.

Some technical working meeting were in the meantime organized, in Zurich, in Karlsruhe and in Tokyo, to discuss and evaluate the progress in the works and to exchange partial results.

The results of the meetings were reported in minutes and sent to all the participants.

Many preliminary data were exchanged among the participants before the preparation of each final report, in order to better address and coordinate the activities.

RESULTS OF THE ANNEX XII EXTENSION

On the basis of the established working program and of the individual tasks for each participant the work carried out in all participating countries can be considered succesfully concluded. Results can be summarized as follows:

- three SPF computer simulation models;
- analyses and experimental data on variable speed scroll compressors;
- performance evaluation of an air-to-air variable speed heat pump;
- experimental analyses of variable speed heat pumps and single speed heat pumps.

One of the SPF simulation models was provided by Switzerland and is for single speed heat pumps. The model is the up-to-date version of that provided during the first phase of the Annex XII.

Two SPF simulation models, provided by Austria and the USA, are for variable speed heat pump systems.

Modelling and experimental data provided by the Swiss participant concern a hermetic scroll compressor operating with R22 in a speed range of 1800-7800 rpm, whose volume displacement is 45 cm^3/rev.

Analyses and experimental data provided by Italy concern two hermetic scroll compressors operating with R22 in a speed range of 2300-6700 rpm, whose displacement is 45 cm^3/rev and 64.2 cm^3/rev.

The experimental and analytical comparison between variable speed heat pumps and single speed heat pumps carried out in Germany concerns two brine-to-water heat pumps: one of the units is equipped with a single speed reciprocating compressor, whereas the other one is equipped with a variable speed scroll compressor.

Performance evaluation tests of an air-to-air heat pump (Hitachi Utopia series) were carried out in the USA by a subcontractor of ORNL.

A series of meetings making great contributions to the diffusion of technical information can also be considered as a result of the Annex.

All contributions are later briefly summarized; nevertheless a detailed description of the activities and results from each participant is reported in technical papers and reports distributed to all the participants.

SWISS SPF COMPUTER SIMULATION MODEL

The Swiss SPF simulation program YUM (Yearly Utilization Model) is a design tool to optimize the Seasonal Perfomance factor of single speed electrically driven heat pump systems, hence improving the competitiveness of such systems.

The heat pump heating system is reduced to the following six basic modules:

- electrically driven air-to-water heat pump based on manufacturer data taking into account the cycling and frost/defrost losses;
- 3-way mixing valve to control the weather dependent supply temperature of the heating system;
- storage tank based on the plug-flow principle, accounting for stratification and heat loss to the environment;
- electric auxiliary heater with a definable start up delay;
- 3-way mixing valve to continuously control the heat pump outlet temperature or the inlet storage tank temperature;
- simplified building model in conjunction with a space heating system considering heater type, building weight, external and internal heat sources, as well as heater capacity at reduced mass flow.

The last two modules differentiate this up-to-date version of SPF simulation model from the first version.

Each module is implemented as a Turbo-Pascal 5.0 procedure using its own structured I/O interface. Thus, the algorithms can be easily modified without changing the structure of the main program.

The program can run on any fully IBM compatible PC with at least two disk drivers or a hard disk and at least 640 KB free memory. Although a Math-coprocessor is not strictly necessary it is recommended in order to reduce running time.

Since the program is always working in text mode, a special grafhic card is not necessary. For a spread sheet program a VGA or EGA resolution might be desiderable to present the grafhics in an appropriate way.

The simulation is carried out by calculating in discrete time step the steady-state behaviour of each module during climatic conditions variation. Climatic data are available for eight regions of Switzerland.

The output results are step wise stored in a data file in order to allow a detailed analysis of them.

The output time step, the step width at which the output data are recorded, is usually considerably larger than the simulation time step in order to save disk space. Thus the arithmetic mean over the output time step is calculated by averaging the results at each simulation time. As the output time step is larger than the simulation time the so calculated mean values have to be used with care, since within the output time step the heat pump can operate at full time, part time or not at all. Thus, temperatures are smoothed and peak values can not be obtained from these smoothed data. To see for example the actual exergetic efficiency of the heat pump it is recommended to set an output time step equal to the simulation time and run the program over a short period of time.

As validation of this model the same deviation calculated for the first version can be assumed. Such deviations were approximately 3% on the SPF, 12,5% on the electricity consumption and 6,6% on the heat gain.

Since the model is built up on modules, different type of heat pumps could be inserted and comparison between them could be done for the same location on the basis of given hourly data for the heat source temperature.

A detailed description of the SPF computer simulation model is in the report "A Yearly Utilization Model for calculating the Seasonal Performance Factor of Electric Driven Heat Pump Systems" distributed to all the participants.

AUSTRIAN SPF SIMULATION MODEL

The work carried out in Austria was principally an experimental work whose results were implemented into the SPF "WPHZB4" model.

The Austrian simulation model is an improved version of that provided in the first phase of the Annex XII. Both measurements carried out in the laboratory of the Institute of Thermal Engineering (Gras University of Technology) and contributions from the USA and Switzerland brought about many improvements.

Whereas the original version of the model was based on hourly values of the climatic data, the present version has been changed to a bin model in order to reduce computing time. Further improvements have been done with respect to the cycling losses as well to the frosting/defrosting losses.

The handling of the model has also been improved by an user interface to provide the input data and run the model based on menu techniques.

The present version includes a variety of integration modes for heat pumps into heating systems.

This model seems to be an excellent tool for the designing of heat pump systems and for the investigation of optimum size and integration mode of heat pump units into hydronic heating systems.

The program is written in FORTRAN 77 language, the compiler and linker use Microsoft FORTRAN 5.0. Graphic adapters implemented into the graphic routines are VGA-16-colours, VGA-Monochrome, EGA-16-Colours and EGA Monochrome.

A detailed description of the program structure, of the subroutines and methods of approach can be found in a very complete final report, "SPF Simulation Model WPHZ", distributed to all the participants with a set of floppy disks.

Installation descriptions and instruction for users are also in the report, including examples of calculations carried out and a lot of diagrams.

Although the program is still a simple model to investigate heat pump systems, it provides very reliable results and a good overview on the effects of modifications introduced in the system in order to improve the SPF.

However, there is still a need for further improvements, especially in the case of continuous capacity control units.

USA SPF COMPUTER SIMULATION MODEL

The ORNL Seasonal Performance Model is designed to compute the seasonal energy input, heating and cooling delivered, and seasonal performance factor for air-to-air heat pumps. The user is required to specify steady-state performance data (e.g. COP and capacity) at two or more ambient temperatures for heating and cooling; several sets of data can be specified to simulate performance of variable speed heat pumps. Binned building loads and weather data are used. Several correlations are available to degrade performance to account for the effects of on/off cycling and frosting/defrosting of the evaporator coil as functions of the ambient temperature and building load. The ORNL model has been validated using measured building loads and weather data for a field test facility in Knoxville, Tennessee.

A floppy disk including code and sample input data has been distributed to all the participants during the working meeting held in Karlsruhe on December 4-5, 1989.

ITALIAN VALIDATION OF ORNL HEAT PUMP DESIGN MODEL MARK III.

ORNL heat pump design model Mark III was used in Tecnars, Italy, to design air-to-air heat pumps. A prototype, splitted into an indoor and an outdoor unit, was accurately built up equipped with pressure and temperature trasducers on the refrigerant circuit.

A reciprocating hermetic compressor, MT 64 manufactured by Maneurop, and operating with R22, was used.

The split heat pump was installed in a two-room climatic chamber where many different operating conditions were simulated; air temperatures (dry bulb and wet bulb) and air flow rate were measured both in the indoor and in the outdoor units.

In order to avoid any heating of the air due to the fans of the heat pump, these fans were not put into operation during the tests and the circulation of the air was achieved by external fans installed in the climatic chamber downstream of the air flow meters.

Experimental measurements were carried out with constant indoor temperatures fixed in the range of 20-30 °C and outdoor constant temperature fixed in the range of 5-18°C. All the operating parameters were measured during each test. The refrigerant mass flow rate was not directly measured but it was calculated on the basis of the electric power input and of the specific enthalpy difference between suction and discharge conditions. The compressor was carefully insulated and shielded from the air flow passing through the outdoor unit.

The experimental results were compared with the predictions of the ORNL heat pump design model that was run under the same climatic conditions of the tests carried out.

The comparison confirmed a good agreement between measured and predicted values, thus showing a satisfying accuracy of the model.

The diagram in fig. 1 shows the measured and calculated COP under different operating conditions.

The maximum observed deviation between measured and calculated values was less than 5% or 1 °K for temperature. The results of the activity are included in a detailed report, "TECNARS Air-to-air Heat Pump Prototype", distributed to all the participants.

SWISS MODELLING AND EXPERIMENTAL ANALYSIS OF INVERTER DRIVEN SCROLL COMPRESSORS.

A theoretical and experimental analysis of the various losses occurring in an Inverter-Scroll Compressor Combination has been carried out at the Laboratory for Energy Systems of the Swiss Federal Institute of Technology-Zurich (ETHZ).

In the theoretical part a model for an Inverter-Scroll Compressor and its characteristic key values were derived.

In the experimental part, suitability and chacteristics of a variable speed scroll compressor were investigated; first, on a special test rig based on refrigerant vapor cycle and subsequently on a full heat pump cycle test rig. The influence of liquid injection on the scroll compressor characteristics was also investigated.

The simulation model for Inverter-Scroll compressor combination, with 16 empirical constants, based on fundamental electrical and thermodynamic relationships can calculate individual losses and phenomena in the combined system.

The inverter losses are calculated as a function of the carrier frequency, the output current and four empirical constants. The scroll compressor model is based on an energy and mass flow balance as proposed by Pandeya and Soedel (A generalized approach towards compressors performance Analysis-proceeding of the Purdue Compressor Conference, 1978) purposely adapted to scroll compressors.

The experimental analysis concerned an hermetic discharge gas cooled scroll compressor operating with R22 in a speed range of 1800-7800 RPM and having a displacement volume of 45 cm^3/rev.

Tests were carried out on a well instrumented air-to-water heat pump installed in a climatic chamber where the air inlet conditions could be controlled in a wide range.

All the operating parameters were measured under several operating conditions and the experimental results were subsequently compared with the predictions of the Inverter-scroll compressor combination model.

The diagram in fig. 2 shows the comparison between the calculated and measured mass flow efficiency.

The comparison between calculated and measured parameters, such as capacity, massflow efficiency, individual losses, rotor slip etc., provided a good agreement and consequently satisfying predictions of the model. The deviation observed as concern heating capacity and power consumption ranges between 1-3%.

All the results and evaluations of the activity carried out are documented in a detailed final report delivered to all the participants on September, 1991.

Experimental data are included in an additional report and stored on a floppy disk, which was distributed to the participants in the Annex XII, as well.

ITALIAN EXPERIMENTAL ANALYSIS OF VARIABLE SPEED SCROLL COMPRESSORS.

An experimental investigation on variable speed scroll compressors, manufactured in Japan, has been carried out in TECNARS, Italy. Two scroll compressors have been sistematically tested and analysed by using a special compressor test rig purposely set up and equipped with high quality instrumentation of proved reliability.

Both compressors investigated, having 45 cm^3/rev and 64,2 cm^3/rev of displacement volume respectively and operating with R22, were driven by a general purpose frequency inverter in a speed range of 2300-6700 RPM.

Many different steady state operating conditions have been simulated with fixed subcooling and superheating, and all the operating parameters, such as mass flow rate, actual rotor speed, volumetric efficiency, heating and cooling capacity, power input, COP, rotor slip, etc., have been accurately measured and analysed.

The effects due to the supply voltage variation have been firstly investigated keeping frequency, evaporating and condensing pressures constant. The investigation aimed at identifying the optimum supply voltage for each frequency; it was carried out with different frequency values and different pressure ratios. The behaviours of the compressors have also been analysed as a function of pressure ratio keeping frequency and supply voltage constant. The analysis was carried out for different constant frequencies and supply voltages.

A comparison between experimental data of variable speed scroll compressors and catalogue data of a single speed reciprocating compressor has also been done, in order to identify the potential benefits of variable speed and the field of application and the conditions under which such benefits are more significant.

The results of the investigation put in evidence the special performances of the variable speed scroll compressors and the effects of the operating parameters such as suction pressure, discharge pressure, compression ratio etc. on the performances itself.

Particolarly interesting has been found the volumetric efficiency that has a relative low sensitiveness to the operating pressure ratio and whose values are well beyond 90% in the greatest part af the scroll compressor's operating range.

The diagram in fig. 3 shows the volumetric efficiency of the bigger tested compressor versus pressure ratio at different frequencies.

Tests also show a considerable impact on the compressor efficiency of a properly selected supply voltage for each frequency.

The diagrams in figures 4.a and 4.b show the measured heating COP versus supply voltage at 40 Hz for both tested compressors.

The experimental data collected constitute a detailed investigation of the performances and of the behaviour of variable speed scroll compressors currently used by Japanese manufacturers to produce heat pump systems.

All the experimental results, the description of the compressor test rig and of the experimental procedure are reported in a complete and detailed final report that includes many diagrams.

In the final report, delivered to all the participants in the Annex XII, there is also a floppy disk containing all the experimental data collected.

Some of the main results arised during the activity are reported in a technical paper "Experimental Analysis of a Water-to-Water Heat Pump with Variable Speed Scroll Compressor" presented at the 10th Purdue International Compressor Engineering Conference.

U.S.A. TESTS OF A VARIABLE SPEED AIR-TO-AIR HEAT PUMP

Test for performance evaluation of a Japanese variable speed heat pump system have been carried out by a subcontractor to ORNL. The tested heat pump is a 8,7 kW coding capacity Hitachi split system equipped with scroll compressor driven by PWM inverter.

Tests were carried out according to ARI Standard 210/240-84 and NBSIR 88-3781 for evaluation of variable speed heat pump system.

Extensive testing in cooling mode and heating mode was done with a frequency analizer connected between the compressor motor and the inverter in order to evaluate the compressor synchronous speeds and to control strategies used by the unit.

In table 1 some results of the heating mode tests are reported.

For the steady state tests the compressor speeds were 30 Hz for low speed and 80 Hz for high speed.

The measured data point out that the performances are not satisfying in comparison with ORNL experience and that the tested unit does not represent the best potential benefits achievable with variable speed scroll technology.

Results of this activity have been delivered, to all the participants in the Annex, during the 7th working meeting held in Karlsruhe on December 4-5, 1989.

GERMAN ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF VARIABLE SPEED AND SINGLE SPEED HEAT PUMPS.

The contribution from Germany to the work of Annex XII consists of an experimental and analytical investigation of variable speed versus single speed heating only heat pumps. The project was supported by the German Research Ministry (BMFT). Results of the project were presented by K. Holzapfel at the Heat Pump conference in Graz 1990 ("An experimental and Analytical Comparison of variable Speed Electric Heat Pumps versus Single Speed Heat Pumps in Hydronic Space Heating systems"). The paper was sent to all the participants of Annex XII.

In this project, the steady state and dynamic performance (COP, and performance factor in a given test period) of two brine-to-water variable speed electric heat pump prototypes, and of two conventional single speed heat pumps were tested and compared.

For the dynamic tests, both the conventional and the variable speed systems were operated with the same heating load that has to be met in an average detached house in Southern Germany. The measurements were carried out on a specifically designed test, stand at Fachhochschule Karlsruhe. The dynamic heating load was simulated by an heat exchanger following hourly values of outdoor temperatures given by the test reference year for Germany Zone 8 (TRY 08). The test reference year data were contributed by "Deutscher Wetterdienst Zentralamt Offenbach".

Since the test for a full heating season would have been too time consuming, two test periods of 5 days each were identified. The "warm" test period was TRY 08, March 19 through 23, which represents very well the average conditions of the total heating season. The "cold" test period is TRY 08, December 17 through 21, representing peak load conditions that are even higher (for a few hours) than design load.

The diagram in fig. 5 show the performance factor versus time during the "warm" test period for the single speed and variable speed tested units.

The measured performance factors, 3.1 for the single speed heat pump and 3.4 for the variable speed heat pump prototype, for the warm test period were considered to be representative for the whole heating season. This assumption was confirmed by simulation runs with the simulation program of H. Halozan (TU Graz). First the program was used simulationg the actual test period which came up with the same result as testes. Second the program was used to simulate the whole heating season based on the TRY 08 weather data. Again the result was equivalent to the measured value of the "warm" test period. This result shows the good accuracy of WPHZ 4. It also shows the improvement in energetic efficiency that can be achieved by using variable speed instead of single speed heat pump heating systems.

It was also shown in the project that further improvements are possible, since the variable speed heat pump prototype needed further optimization. In particular the automatic control of the expansion valve caused a number of problems in conjunction with the automatic control of the frequency inverter. Manual operation showed considerable better results than the automatic operation during the performance factor tests.

CONCLUSIONS.

Many activities have been succesfully carried out by the participants in the Annex XII, and many reports and technical papers have been produced and provided.

During the first phase of the Annex, when ORNL served as Operating Agent (see attached report by S. Fisher), three computer simulation models for heat pumps were supplied by Austria, Switzerland and USA, and three sets of field data (two from Switzerland and one from the USA) were also supplied. On the basis of the data the validation of the US and Swiss models were performed.

Italy contributed the validation of the ORNL Heat Pump Design Model MARK III.

During the second phase of the Annex, coordinated by Tecnars - Italy as Operating Agent, activities were focused on variable speed electric heat pumps in order to investigate the potential benefits of this technology by utilizing and adapting existing simulation programs. For this task three APF simulation programs were supplied by Switzerland, Austria and the USA. This task also required extensive experimental work that was carried out in Austria, Germany, Italy and Switzerland in order to gain more hard facts on the behaviour of variable speed compressors and complete heat pump systems.

The available models, when fed with accurate compressor data, reached a good prediction of COPs and APFs of single speed systems. For variable speed systems the same applies, it has to be noted that the set of necessary compressor performance data is much more extensive. These data have to relate the compressor output to the electric input to the frequency inverter.

The investigation of the variable speed technology showed a considerable improvement potential for example in terms of energy efficieny, depending on the operating conditions in a given application. It further indicated the need for system design optimization with respect to the particular behaviour of variable speed systems differing widely from well known single speed systems. In this respect, major points of interest besides compressor and inverter are expansion valve design and control, inverter control strategies, load depending voltage control, heat exchanger and piping design and sizing, etc.

Although many activities have been done, and even very carefully, the delay in achieving the results, due to several reasons, including the limited amount of the budget, is to be unfortunately considered as a negative point.

As a matter of fact, the delay caused a non in-depth interaction between experimental results and modelling

The whole activity of the Annex XII, however, has been considered very valuable by the participants and it is worth to be continued with further developments of variable speed systems.

For this reason a new strategic plan and those actions considered strictly necessary for a deep technical knowledge should be defined.

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4. T. Afjey - "Modelling and Experimental Analysis of inverter driven Scroll Compressors". Swiss Report.

5. V. Bruno, V. Recchi - "Experimental Analysis of Variable Speed Scroll Compressors". Italian Report.

6. ORNL - "Tests of variable speed air-to-air heat pump". USA Tests.

7. K. Holzapfel - "An experimental and analytical comparison of variable speed electric heat pump versus single speed heat pumps in hydronic space heating systems". German contribution - paper presented at the Heat Pump Conference in Graz, 1990.

8. V. Bruno, K. Holzapfel - "Experimental Analysis of a water-to-water heat pump with variable speed scroll compressor". Paper presented at the 10th Purdue International Compressor Engineering Conference.

9. ORNL - "Annual Performance factor/loads (APF) Model for single and variable speed heat pumps". USA contribution.

Table 1. Results of Heating Mode Tests (1)

Test	Compressor Speed (Hz)	Outdoor Temperature (°F)	Measured Quantities to be Used in Calculation Procedures					
			Capacity (Btu/hr)		Energy Input (W)		COP	
			Rated (3)	Measured	Rated (3)	Measured	Rated (3)	Measured
Steady-State	30	62	18,000	18,000	>1,600	1,630	<3.3	3.2
Cyclic (2)	30	62	—	2,966 Btu	—	387 W·hr	—	
Steady-State	30	47	16,000	14,100	1,600	1,540	2.9	2.7
Steady-State	80	47	36,000	30,500	5,800	4,140	1.8	2.2
Frost Accumulation	80	35	28,000	23,200	—	3,840	—	1.8
Frost Accumulation	46	35	—	18,500	—	2,300	—	2.1
Steady-State	80	17	27,000	19,000	<5,200	3,300	>1.5	1.7

$C_D = 0.38$

(1) Tests were conducted according to NBSIR 88-3781. Exact conditions held during tests are presented in Table 2.
(2) 10 min. on/ 40 min. off, constant low speed fan operation during off period (this is the control used in by the manufacturer).
(3) Compressor speeds used by Hitachi in rating the equipment are unknown.

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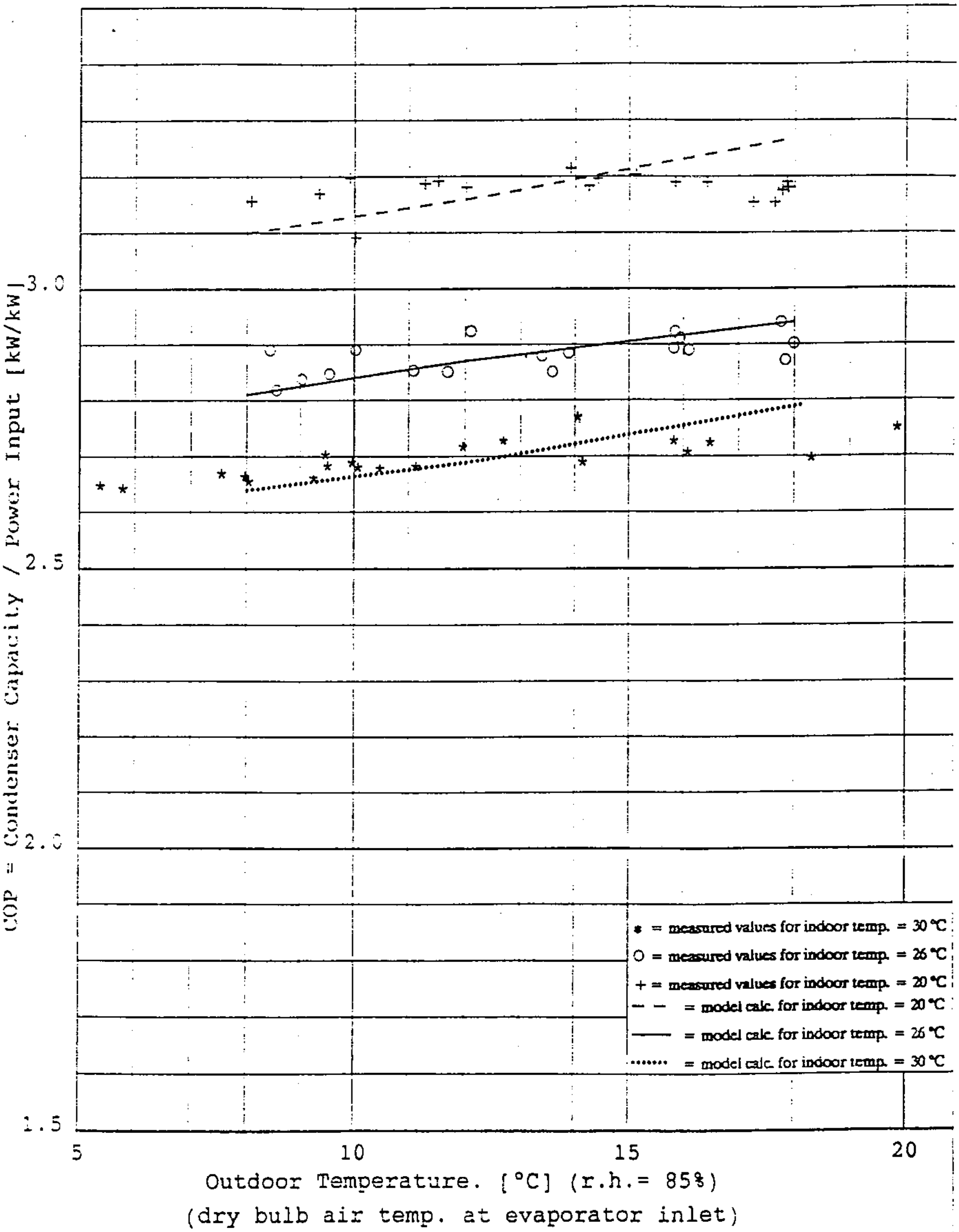
FIG. – 1 – Heat Pump COP

Basis for model: Compressor Measured Data - 12 % quality



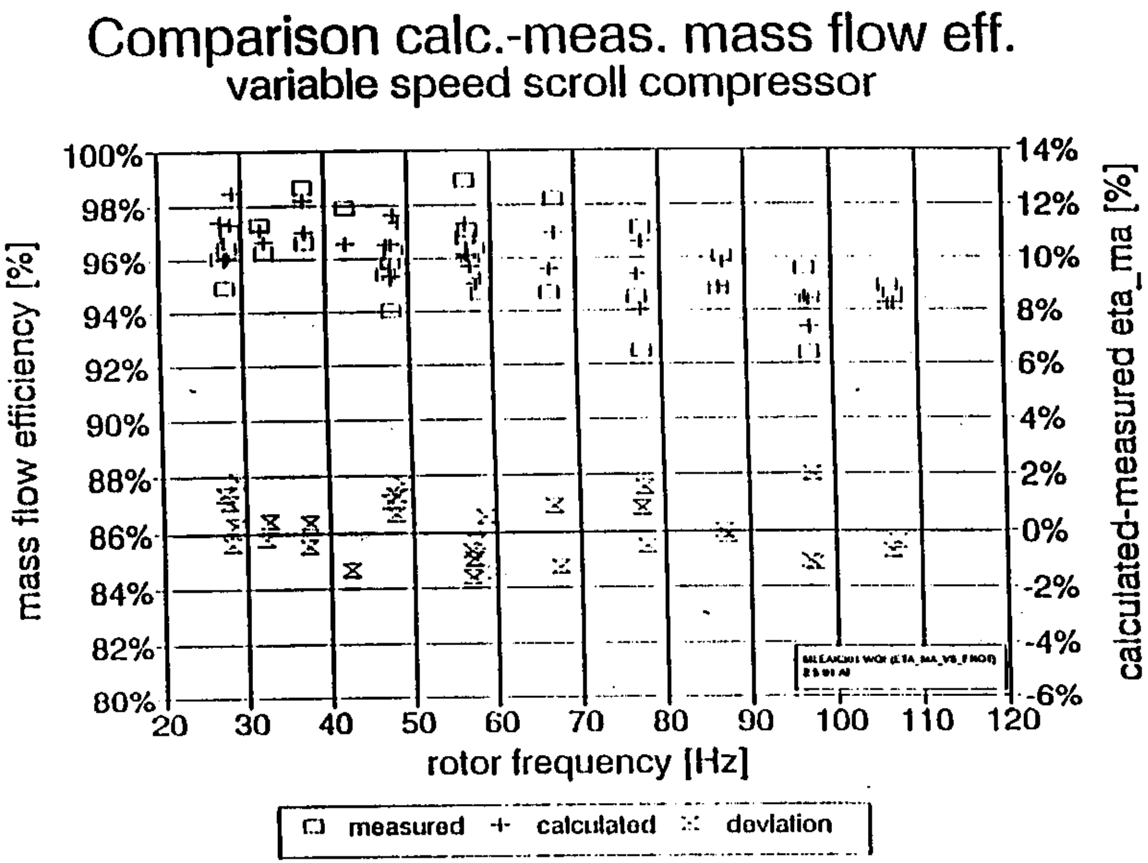


FIG. — 2 — **Comparison between Calculated and Measured Mass Flow Efficiency**

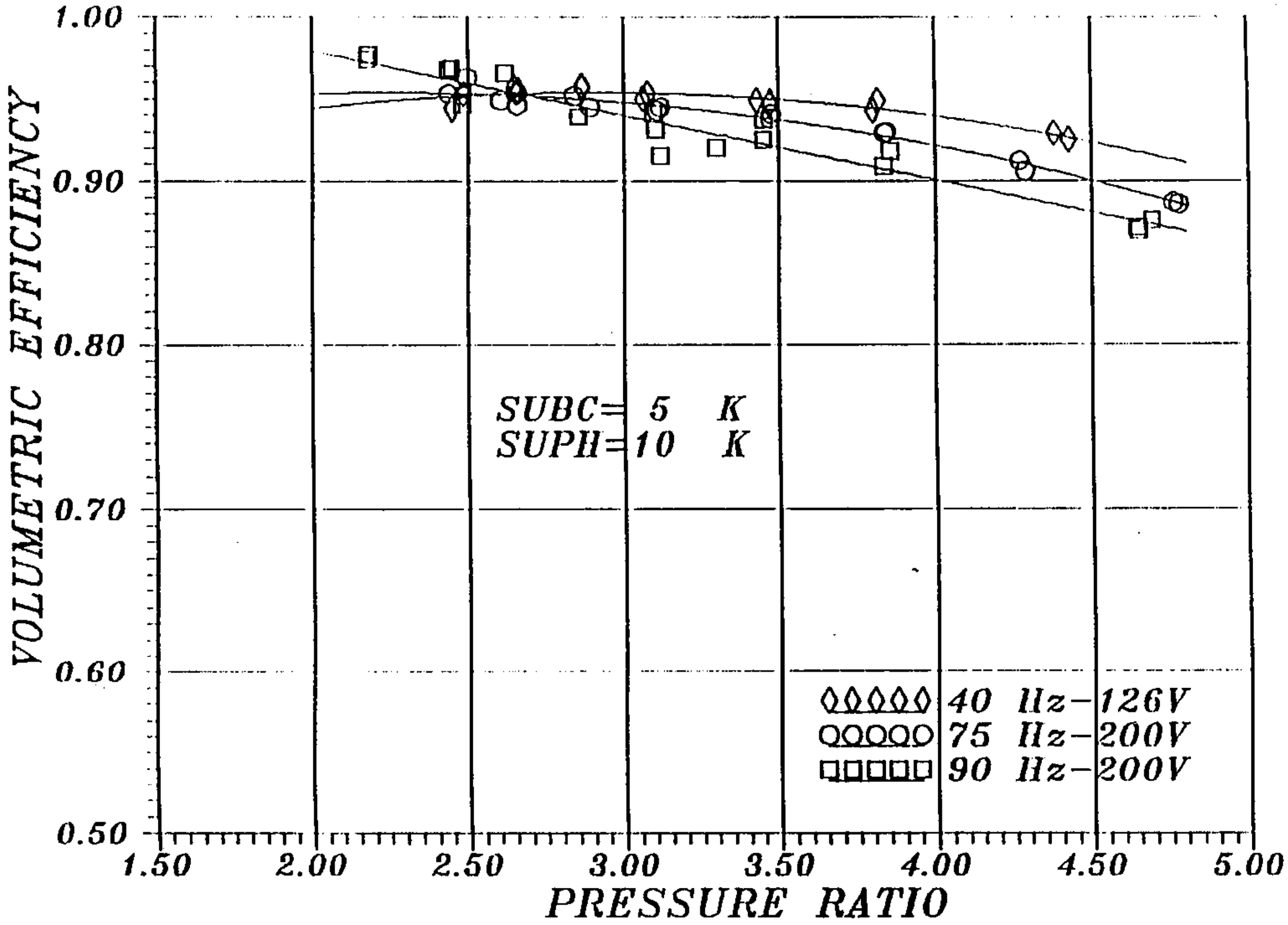


FIG. -3- Volumetric Efficiency versus pressure ratio at different frequencies

COND. SAT. PRESS.=1.72 (MPa abs.)

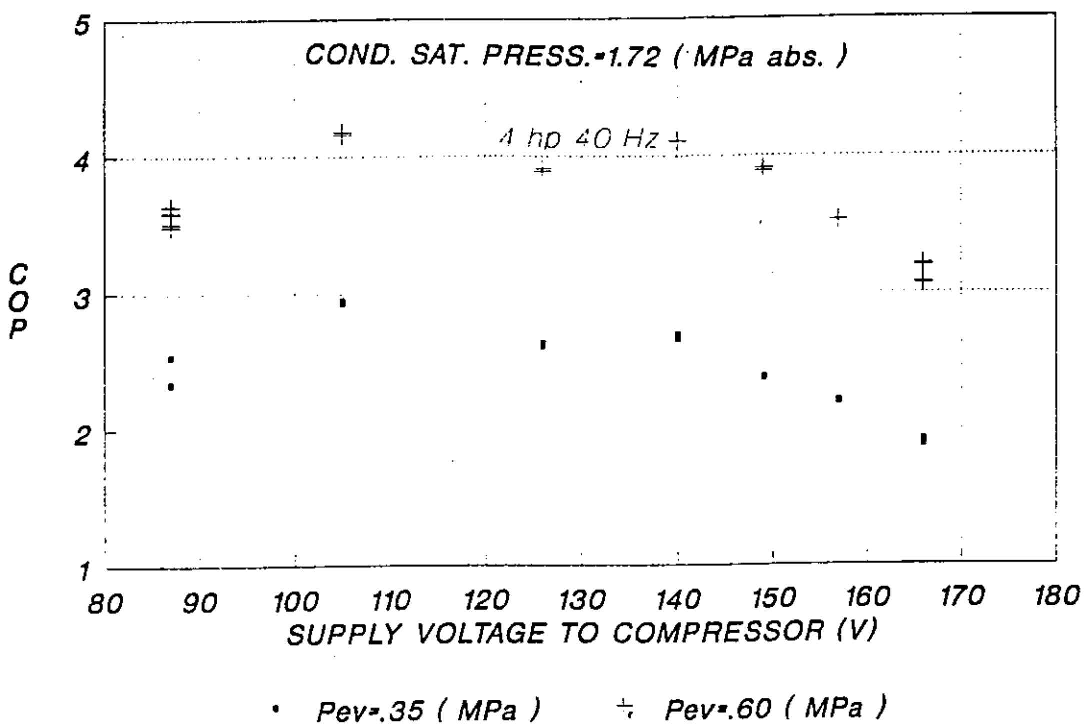


FIG. -4A- Heating COP versus supply voltage for the smaller tested scroll compressor

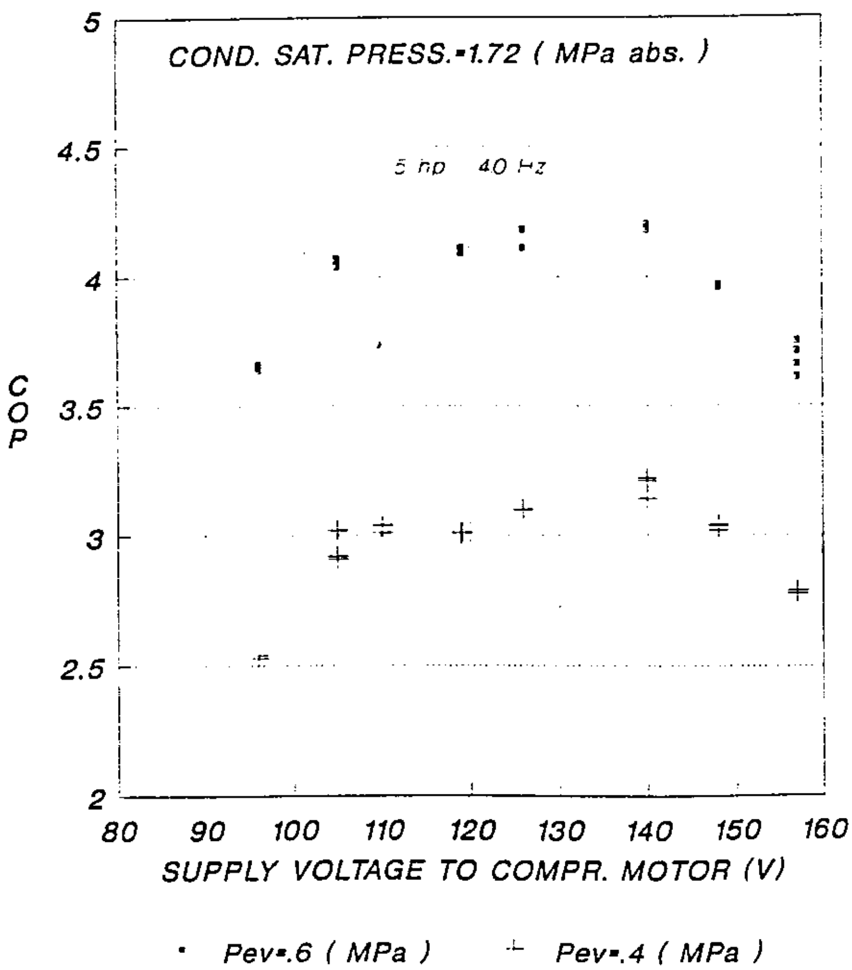


FIG. -4B- Heating COP versus supply voltage for the bigger tested scroll compressor

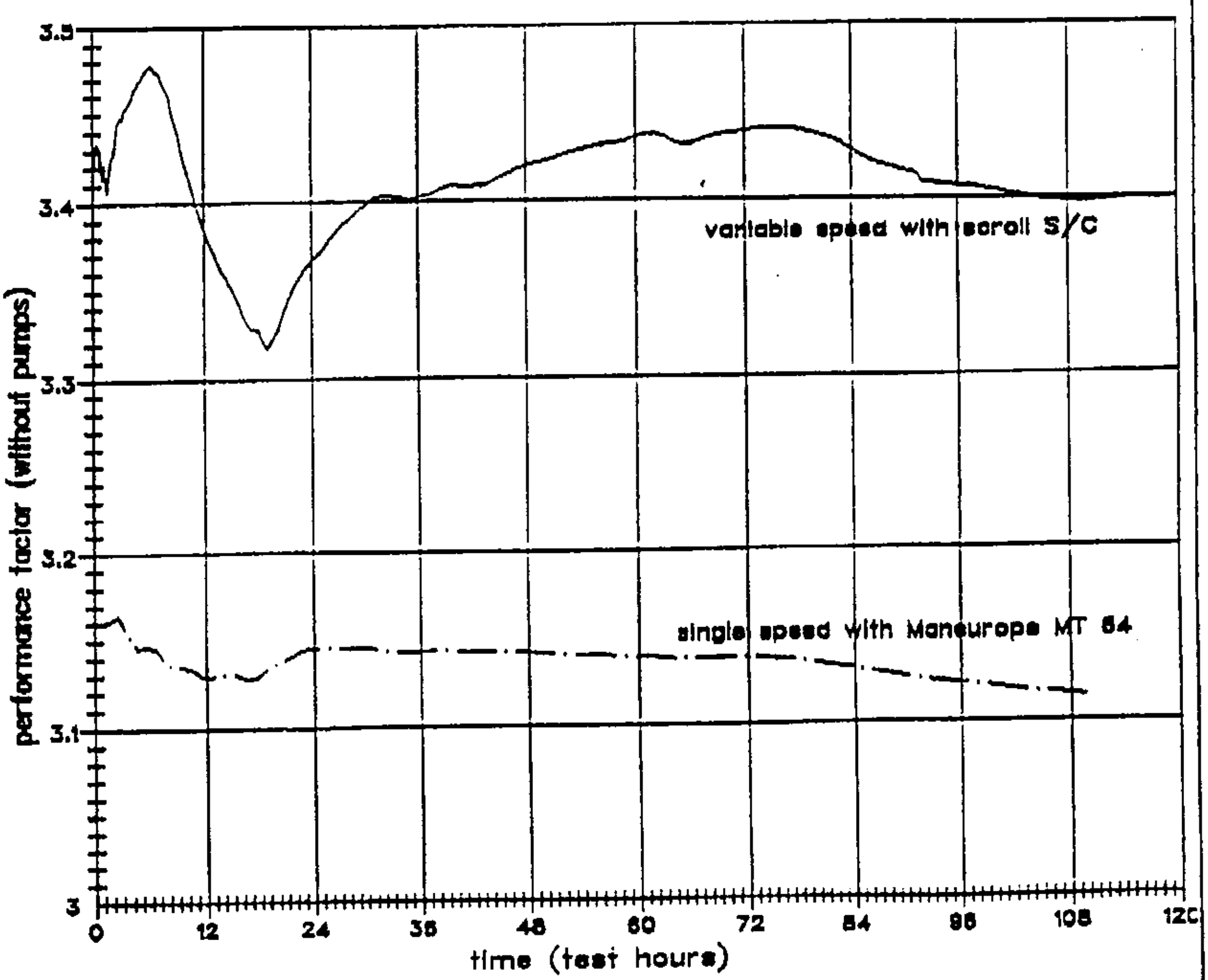


FIG. 5— Performance factor for both test heat pumps during "warm" test period

ATTACHMENT 1

INTERNATIONAL ENERGY AGENCY PROGRAMME OF RESEARCH AND DEVELOPMENT

ON ADVANCED HEAT PUMP SYSTEMS - ANNEX XII

MODELLING TECHNIQUES FOR SIMULATION AND DESIGN OF COMPRESSION HEAT PUMPS

FINAL REPORT

November 23, 1988

INTRODUCTION

Annex XII was established as a working group to evaluate the state of computer modeling of heat pump systems in the participating countries. In the official language of the Implementing Agreement, the objective of this annex is to:

> "... assess the adequacy of existing techniques for modelling the seasonal performance of compression heat pumps and to define the needs for additional fundamental information and research needs."

Also from the Implementing Agreement:

> "the results of this Task shall be interim reports and a final report integrating the results and presenting conclusions on the adequacy of existing techniques and recommendations for additional co-operative work, if appropriate."

Seven countries participated in the annex: Switzerland, Austria, Belgium, the United States, Japan, the Federal Republic of Germany, and Italy. The United States served as Operating Agent for the annex.

The adequacy of the existing modelling techniques was determined by evaluations of computer programs contributed by the participants and comparisons of their simulated performance with actual data measured in field experiments. Three different computer models were contributed which are suitable for simulating the seasonal performance of electric air-source heat pumps. Three sets of field performance measurements were also contributed which could be used to evaluate the accuracy of the simulation models. Numerous technical papers were also contributed to the annex to assist in developing techniques and algorithms for improving model predictions. Each of these is described in greater detail in the following sections of this report.

Two of the seasonal performance models have been validated by the countries that contributed them against field performance data. Each predicted the heating season performance factor within about 5% although neither did as well for every individual month because under predictions of energy use in some months compensated for over predictions in others. Generally speaking monthly simulations were within 5-7% of measured performance except in the "shoulder" months where there were greater cycling losses. This is particularly true of the one model which does not account for on/off cycling of the heat pump.

Three questions arise in determining what further research needs exist in the computer simulation of heat pump seasonal performance: 1.) what degree of accuracy is required, 2.) what improvements can be made to the models to achieve higher degrees of accuracy, and 3.) what additional "features" are needed in a computer model. The first point must be addressed by each individual based on his own specific requirements; what is satis-

factory for one person's needs may be inadequate for another's. Generally speaking, the accuracy would be improved by refining the algorithms used to computer losses due to frosting, defrosting, and cycling, although this would be at the expense of the time required to model a heating season and also the versatility of the program. It may be possible to simulate the performance of one particular heat pump very well because the correlations used are very specific to that design, but be unable to model a slightly different machine adequately.

Capabilities in computer simulations have not kept up with developments in the design and construction of heat pumps in that none of the models here has a demonstrated ability to simulate the performance of a modulating, or variable-speed, compressor or fan. Each of the participants in the annex viewed this as a desirable or necessary feature in order for computer modeling to be a valuable tool in developing new equipment. Two of the computer models include initial efforts at simulating heat pumps with variable speed compressors but each could use validation and refinement. At present there are very little data available on steady-state or seasonal performance of variable-speed heat pumps. There is some information in the technical papers contributed to the annex which can be used to refine the steady-state calculations and the frosting, defrosting, and cycling degradations in these models. Additional data are needed for validation.

COMPUTER MODELS

AUSTRIAN MODEL

The Austrian Model simulates the performance of a heating system consisting of a heat pump (or heat pumps), conventional boiler, and a hydronic distribution system. It does not simulate cooling performance. Several heat pumps can be used, either in parallel or series configurations, and they can use either air or water as the heat source. The water-source heat pumps can use ground water, have ground-coupled evaporators, or be solar assisted. The model includes the capability of buffer storage and accounts for hysteresis in the distribution system. The heat pumps can be single-speed, step-modulated (up to four steps), or have continuously variable-speed capacity control.

It incorporates a steady-state evaluation of the heat pump performance and applies degradation factors to it to account for dynamic losses. The calculations can be done on an hourly basis for the entire year or using temperature bins for the building loads and outdoor temperatures.

Degradation factors for dynamic losses are used in a straightforward, simplified manner. Reduced performance due to frosting of the evaporator is evaluated by multiplying the steady-state heat pump capacity by a fixed percentage (0.92 is used in the sample data provided) at all temperatures below a certain, specified temperature where the onset of frosting occurs. Defrosting is handled in a similar manner, in that the heat pumps power requirements are multiplied by a fixed factor (1.08 in the sample data) at all temperatures below the frosting point. Additional power required due to on/off cycling is computed by estimating the number of system start-ups and then adding a specified fraction (0.08 in the sample data) of the steady-state power for each start-up. Pumping power for the distribution system is assumed to be included in the specified heat pump and boiler performance data. Supplemental, backup heat is assumed to be from a gas or oil fired boiler.

The Austrian model is written in FORTRAN-77 and is relatively short and concise compared with the Swiss and U.S. models. It employs either of two main programs, depending on whether the binned or hourly calculations are desired, and uses five subroutines. There are two additional programs to assist in preparing the weather, loads, and heat pump data. The program requires just about 86K of random access memory (RAM) and works easily on an IBM PC or compatible personal computer from either a floppy disk or from a hard disk.

Although some FORTRAN compilers do not require the use of a math coprocessor (8087 or 80287) it is recommended that one be used with this program. The version of the model working with temperature bins runs very quickly (1 to 2 minutes for the sample case provided with the code) on an IBM PC, but the hourly version takes significantly longer (10 to 12 minutes). These times would be much longer for a PC without a math coprocessor (these times were not measured).

The data for the heating capacity and power requirements of the heat pump are specified as six coefficients for a polynomial fit in the source and sink temperatures. Step-modulating performance is computed by specifying different multiplicative constants to be used with the same polynomial fits. As mentioned earlier, fixed multiplicative constants are used to degrade performance for cycling, frosting, and defrosting.

Building loads can either be computed as a multiple (or fraction) of the building design load or they can be read in as specified data (along with the water temperatures returning to the heat pump). The required weather data can be read either as hourly data or binned data.

U.S. MODEL

The U.S. model is designed to simulate the annual performance of an electrically driven, air-source heat pump with a forced air distribution system. It models both heating and cooling performance. The heat pump can have a single, fixed design heating capacity, be step-modulated, or be continuously variable capacity. It uses binned temperature and building loads data and has the capability computing the building loads from building structure and weather data.

The model employs a straightforward, steady-state analysis with degradation factors applied to simulate the frosting, defrosting, and cycling losses of the heat pump. Algorithms are built into the program to compute these losses based on measurements taken at the U.S. National Bureau of Standards (NBS), Oak Ridge National Laboratory (ORNL), and the U.S. Department of Energy (DOE) rating procedures. The user can modify the coefficients used in these algorithms as desired. Supplemental heat required below the system balance point is assumed to be provided by electrical resistance heaters.

This code was originally written in FORTRAN IV for use on a mainframe computer although it has been adapted for use on an IBM PC and compatible computers. The program consists of 38 subroutines and 28 common blocks for data transfer. It is thoroughly documented in a draft report to assist the user in preparing data, modifying the subroutines, and understanding computed results.

The program requires 296K RAM on an IBM PC (in addition to the system requirements and any memory resident utilities). The size of the program, and the number of computer files involved, demand the use of a hard disk. It is possible to run the code from floppy disks, but it is very difficult to modify it and relink with the libraries using just floppy drives. It is distributed on five double-density floppy disks which include the source code, a library of object modules, an executable file, and sample data files. A math coprocessor is recommended as with the Austrian model.

The heat pump performance data are specified as pairs of points for temperature and capacity and for temperature and power. As many as ten points can be used to describe each curve (heating or cooling capacity and heat pump power input). Multiple sets of curves are used to simulate step-modulating or continuously variable-speed heat pumps. Linear interpolation, or extrapolation, are used between data points along curves for single-speed or step-modulated heat pumps. Interpolation between curves is performed for continuously variable-speed systems.

As mentioned earlier, several different algorithms are provided for frosting, defrosting, and cycling losses and each of these includes suggested values for the necessary coefficients and temperatures. Frosting losses are computed over a limited range with an upper and a lower limit on the temperatures where frosting is assumed to occur. The user accepts or specifies the temperatures to delimit this range and also the intermediate point of maximum frosting. Defrosting can be modelled based either on a demand or time-temperature criteria. Two different algorithms based on measurements at NBS and ORNL are available for degrading performance due to cycling. The DOE, C_d method can also employed to estimate cycling losses and separate coefficients can be used for heating and cooling computations.

The program uses monthly, binned weather data and building loads. Building loads can be computed, as an option, by specifying simplified building construction information (e.g., U-values for walls and windows, wall areas, building orientation). Several sample data sets are supplied with the program.

This program includes a section in the calculations that estimates how much energy would be used under steady-state heat pump operation, how much more is required to compensate for frosting, defrosting, and cycling losses, and how much backup heat is used. A BASIC program is provided which can be used to make a pie chart of this energy use breakdown.

SWISS MODEL

The Swiss seasonal performance model simulates the performance of an electrically driven, air-to-water heat pump with a hydronic distribution system. The heat pump is used to store heat in a large tank and then a separate loop is used to circulate water from the tank throughout the building. An electric, resistance heater is employed in the building loop to ensure that the water delivery temperature remains above a specified minimum temperature.

The program performs a combination of transient and steady-state calculations. The accumulation of frost on the evaporator coils is modelled in a transient manner with fixed time steps specified as fractions of an hour. Polynomial fits are used to estimate the steady-state operation of the heat pump as functions of the ambient air temperature and the water temperature entering the heat pump. Either a demand defrost algorithm, based on pressure drop across the evaporator, or a time-temperature defrost scheme can be used. The heat required to defrost the evaporator is computed based on assumptions about a hot gas bypass defrosting mechanism. Supplemental resistance heat is used as required. The program does not account for on/off cycling losses.

The Swiss model is written in Turbo-Pascal for use on an IBM PC. As such it requires only 64K of RAM. The program has been written to use two floppy disk drives, although the users' manual explains what modifications are required to run it from a hard disk. The original program can be run on a system with a hard disk by using the ASSIGN command available in PC-DOS 3.1 and higher.

This program is large, on the same scale as the ORNL model, and uses 39 Pascal procedures and 21 functions. There is also a graphics option that adds 10 more procedures and an option for computing the required polynomial correlations that has two additional procedures. The program is distributed on two double-density floppy disks, with both source code and executable programs. Additional disks are provided with sample data.

Although Turbo-Pascal does not require a math coprocessor it is highly recommended for this program. The transient calculations for frost formation require a great many computations, even for a 24 hour simulation, and the math coprocessor can reduce the execution time by a factor of 10 or more (actual comparison for a 24 hour simulation using the sample data provided with the model).

Data for the steady-state heat pump performance, capacity and power, are computed based on polynomial approximations in the ambient wet-bulb temperature and the condenser discharge water temperature. The coefficients can be read from a data file or they can be computed within the program by interactive entry of manufacturer's performance data points. The heat pump data also includes the water pumping power between the heat pump and the storage buffer.

The frosting algorithm requires eight coefficients, two each for correction factors for the heating capacity, the electric power demand, the refrigeration rate, and the air volumetric flow rate. These parameters are machine dependent and will vary with the evaporator dimensions, fin spacing, fan size, etc. Sample values are provided for a particular heat pump based on Swiss laboratory measurements.

Hourly building loads and weather data are read by the program. The weather data includes the time, barometric pressure, and dry bulb and dew point temperatures. This is the only program contributed to Annex XII that uses both dry bulb and enthalpy data to compute frosting losses. A data file is also required that describes the storage buffer and distribution system, including pumping power from the tank to the building.

FIELD DATA

SWISS FIELD DATA - FIRST SET OF DATA

The first set of field data contributed by Switzerland is for an "integrated" heating system in a single family home. An air-to-water heat pump is used for space heating, heating an outdoor swimming pool, and to preheat domestic hot water. An 800 liter tank is used for thermal storage and preheating the domestic hot water. These data were taken between September 1979 and September 1980, although there are gaps in the data, most notably from mid-December through the first of March.

The measurements in this set of data were taken at one minute intervals with average values recorded every 15 minutes. The data include the heat provided by the condenser, the heat delivered from the storage tank, heat provided to preheat domestic hot water, integrated compressor and fan power, indoor and outdoor dry-bulb temperatures, and water temperatures throughout the system. Enthalpy measurements of the air (relative humidity or wet-bulb temperatures) were not taken in this experiment.

The heat pump used in the experiment is described in the report *First Set of Swiss Field Data* provided to the annex. This includes catalog performance data for the heat pump (as functions of the water temperature leaving the condenser and the outdoor air temperature) as well as a complete description of the defrost control system.

SWISS FIELD DATA - SECOND SET OF DATA

The second set of Swiss field data is for a school in the Zürich canton of Switzerland. The heating system consists of two air-to-water heat pumps operating in tandem with two oil fired boilers. The lower capacity heat pump is set up either to reclaim heat from the ventilation system of the building or to use outside air as a heat source. The second heat pump uses solely outside air.

Measurements were recorded hourly for the entire 1986-1987 heating season. They included the time of day, the electrical energy use of the compressor and fan, the thermal output, the condenser water flow rate, the condenser outlet and inlet water temperatures, the ambient air temperature, the temperature and relative humidity of the air entering the evaporator, the air temperature at the evaporator exit, and the fractions of time the circulator pump and compressor were on.

The steady-state and defrost control systems of both heat pumps are documented in the report *Second Set of Swiss Field Data* provided to the annex. As with the first set, this report is a thorough description of the heat pumps and the measurements taken.

U.S. FIELD DATA

The U.S. field data were taken at the Tennessee Energy Conservation in Housing (TECH) experimental station near Knoxville, Tennessee. The site consists of three nearly identical single family homes with instrumentation connected to a single computerized data acquisition system (DAS). The houses have the same floor plan, construction materials, and solar orientation so the heating and cooling loads should be the same for each of them. One house was originally heated with solar energy and consequently is slightly different in design. Two of the homes are unoccupied with resistance heaters to simulate internal heat gains. The third house was occupied by a university graduate student and his family to provide security and minor maintenance on the site. The data contributed by the U.S. is for October 1979 to September 1980 and includes both heating and cooling loads, energy use, and weather conditions at the site. The energy-use measurements in this data set are from one of the three homes while the building loads are for another one.

The heat pump installed at the test site was a high efficiency air-to-air system of the late 1970's from one of the major U.S. manufacturers. The steady-state performance of the unit, as installed, is listed below.

	Temperature (°C)	Capacity (kW)	COP
Heating:	-8.3	5.57	2.12
	8.0	10.34	2.97
	9.7	10.90	3.08
	15.6	11.87	3.20
Cooling:	23.4	10.54	3.12
	30.8	10.00	2.80
	40.5	8.26	2.00

Steady-state operation of electric heat pump used for U.S. field test.

The heat pump employed a time-temperature defrost control scheme with a 90 minute cycle. It had an average field measured time of defrost of 4.9 minutes with 8.6 kW of tempering heat during the defrost period. The heat pump used a reverse-cycle defrost process which provided a measured, average cooling during defrost of 4.15 kW. The heating C_d of the heat pump was 0.24 and the cooling C_d was 0.11.

Measurements were recorded by the DAS every hour. Some observations, such as ambient temperatures, were instantaneous measurements while others, like energy use, were cumulative over the time period and then recorded hourly. The data provided to the annex is only a subset of the measurements taken and includes the outdoor dry-bulb and wet-bulb temperatures (°C), the indoor dry-bulb and wet-bulb temperatures (°C), the heating or cooling delivered (W), and the energy input (W) in a 6F8.1 format. The data given to the annex are recorded monthly, with a separate disk file for each month, with one line of six numbers for each hour of each day, beginning at 1:00 am.

VALIDATION OF MODELS

Any assessment of the adequacy of existing models must be based on how well they predict heat pump energy use. Mr. Conde of Switzerland and Mr. Rice of the United States have each devoted effort to determining the accuracy of their own computer simulations and examining their strengths and weaknesses. The Swiss program, YUM, was validated against the second set of Swiss field data contributed to this annex using transient calculations and also a binned analysis. The U.S. validation was performed using a binned algorithm and two different sets of field measurements, those for October 1979 to September 1980 that were contributed to this annex and also heating and cooling data for October 1982 to September 1983.

SWISS MODEL VALIDATION

Mr. Conde has documented his work on model validation in a 19 page report entitled *Validation of the Simulation Program "YUM" against the Second Set of Swiss Field Data*. The YUM program was used to simulate the heat pump operation for the entire 1986-87 heating season using a 12 minute time step. This was a very time consuming process and it was broken down into simulations of one month at a time. The manufacturer's catalog data were used for the steady-state heat pump performance based on the ambient air temperature and the condensing temperature and the effects of evaporator frosting and defrosting were computed using the transient calculations built into the Swiss model.

Comparisons were made between measured and computed values for the input (drive) and output (thermal) energies, the monthly and seasonal COPs, and the heat pump run times. In general there was very good agreement for the thermal outputs except in the months with heavy frosting, which would suggest that the computational algorithms overestimate the effects of frosting. The YUM code systematically underpredicts the compressor drive energy. This is in part due to the fact that there are no losses imposed for on/off cycling, but it could also be due to the use of the catalog data for steady-state performance instead of measured performance for the installed system.

Overall, YUM underpredicted the thermal energy output by 6.6%, the drive energy input by 12.5%, and came within 2.7% of the measured seasonal COP. System performance was also computed using a binned analysis, using 2°K temperature bins, but the results were not as close to the measurements as they were for the hourly simulations, as was expected. The binned analysis systematically overpredicted the thermal output relative to the field data, though it did as well or better at predicting the drive energy as did the hourly calculations. The COP predictions for each month were much further from the observations than they were for the hourly validation. The strength of the binned analysis lies in the speed of the simulation. The entire heating season could be modeled in 30 minutes using the binned algorithms but required 90 times as long using the transient calculations.

U.S. MODEL VALIDATION

The U.S. Annual Performance Factor (APF) model was validated against measured heat pump performance for the 1979-80 heating and cooling seasons and the 1982-83 seasons. Actual "as installed" steady-state capacities and COPs were measured and used for these validations instead of relying on the manufacturer's published performance data. This program uses binned weather and loads data and 5°F temperature bins were used in this analysis. The U.S. DOE Cd procedure was used for on/off cycling penalties and two different algorithms for frosting losses were tried, one based on ORNL measurements and one using correlations developed at the U.S. National Bureau of Standards. This code is set up so that the thermal energy output is always equal to the building load (except when the cooling capacity is insufficient to meet the load), so only input energy and COPs were computed and compared to the observations.

Details about the validation process are contained in the draft report *The Oak Ridge Heat Pump Models: II. An Annual Performance Factor / Loads Model for Residential Air-Source Heat Pumps* by C. Keith Rice, et al. This report contains a discussion of the strengths and weaknesses of each set of field data and an explanation of techniques that were used to screen out bad or suspicious data points. There are also explanations of the two different frosting algorithms, though the differences in results are not sufficiently different to be of great interest here. Overall the results for the 1982-83 calculations were closer to the field data than were those for the 1979-80 simulations. The projected energy input was approximately 4% too high for the 1982-83 heating season and 5% too low for the cooling season. The offsetting errors caused the calculated annual energy use to be within about 1% of the measured value. The corresponding energy use for 1979-80 was 6.5% too high for the heating season and 6% too low for the cooling season.

The field data for 1982-83 was collected in such a way as to differentiate between energy use for steady-state operation, on/off cycling, frosting and defrosting, and to count the number of defrost cycles for the year. The ORNL APF/Loads program includes estimates of each of these parameters that could be compared with the field observations. The calculated energy use for steady-state operation was 1.2% higher than the measured value for the heating season, 6.1% too low for frosting/defrosting, and 25% too high for cycling. The number of defrost cycles (790) was predicted to within 1%. It is believed that the value of Cd used for this heat pump may have been too large and could have contributed to the overestimate of the cycling losses. This possibility is explored further in the report mentioned earlier.

CONCLUSIONS AND RECOMMENDATIONS

Any conclusions concerning the adequacy of the existing heat pump models are going to depend on what is trying to be done with the programs. The consensus of opinion is that:

- accurate simulations of continuously variable-speed heat pumps are needed for future design analyses,
- transient calculations are needed for modeling on/off cycling, and
- more accurate algorithms are needed for frosting and defrosting.

If it is extremely important to get very accurate predictions of energy use and seasonal performance then the existing models are not accurate enough. The U.S. model probably cannot be made much more accurate than it currently is because of the algorithms it uses for binned weather and loads calculations. Clearly the transient simulations have an inherent advantage in accuracy, as shown in the Swiss validation work, and that it probably is not possible to achieve more precise results without working with even smaller time steps and detailed cycling calculations. Although it may be somewhat too severe in its frosting losses, the Swiss model for frosting/defrosting does very well. This is achieved by providing significantly more detailed information about the heat pump in the form of coefficients for four curve fits and at the cost of a tremendous increase in computational time. A physically based simulation of on/off cycling will also require more data and more computing power. This degree of detail is needed to thoroughly understand the dynamics of frosting, defrosting, and cycling.

On the other hand, this degree of accuracy may not be needed if the programs are going to be used to compare the predicted performance of one heat pump to that of a system which is only slightly different. The U.S., for instance, has employed its model in numerical optimizations that require computations at thousands of system designs. This form of analysis would be completely impractical using the very accurate transient analysis.

The annex participants are in agreement that further model development and validation is needed for variable-speed heat pumps. The U.S. and Austrian models include the capability of using specified steady-state data for step-modulating and continuously variable-speed systems but neither has been validated or used extensively in these modes. Accurate methods are needed for predicting the steady-state performance of variable-speed heat pumps before seasonal performance calculations can be made to evaluate the energy use of machines that have not yet been built and tested. A major obstacle facing this development is the inadequacy of data for system and component performance under part load conditions. Extensive testing and evaluation of compressors and variable-speed motor drives are needed to provide these fundamental data so that steady-state heat pump performance can be predicted accurately.

TECHNICAL PAPERS

1. Modelling for Variable Speed Heat Pumps, Belgium

This paper describes an analytical study of variable-speed, inverter driven air-source heat pumps. The compressor speed is allowed to vary between 900 and 3600 rpm producing capacities of 1.3 to 6 kW at 15°C outdoor and 21°C indoor temperatures. The building load is assumed to be linear between 6 kW at -10°C and 0 at 15°C. The heating capacity is assumed to be linear in both speed and temperature while the COP is linear in temperature and parabolic in compressor speed. The paper describes two different computer models written in BASIC for a Hewlett Packard computer. The first performs a rigorous analysis of the frost formation on the evaporator coils with water vapor contributing both to increasing density of the frost as well as the thickness of the layer of frost. Two different analytical models of the defrosting process were examined with this program. The second program examined the optimal working conditions of a variable-speed heat pump and backup heating system for each outdoor air temperature. The economic benefits of variable-speed heat pumps for two case studies are examined.

2. Basic Approach to the Method for Calculating the Annual Performance Factor of Room Air Conditioners, Japan

This report contains guidelines for the evaluation of heat pump annual performance. It is based on the U.S. Department of Energy (DOE) approach with modifications to take into account Japan's regional characteristics, housing structure, and the actual state of usage and function of heat pumps in Japan. Standardized test conditions are given and heating seasonal performance factors are computed in three different ways. A simplified test method is considered which reduces the testing requirements placed on manufacturers. The report includes 26 pages of tables, figures, test results, and SPF calculations.

3. Japanese Industrial Standard (Draft): Testing and Calculating Methods for Seasonal Efficiency of Room Air Conditioners - 1984, Japan

The report summarizes standardized test conditions and methods for calculating season energy efficiency. Standard conditions are given for steady-state performance, defrost, low temperature, and cyclic operation tests. Calculational procedures are given for both heating and cooling season energy efficiency ratios for single-speed, step-modulated (dual compressor) heat pumps, and continuously variable speed controlled heat pumps. The paper includes correlations for frosting/defrosting losses and C_d for cycling.

4. Report on the Research Program for Standardization of Energy Saving Type Household Heat Pump Type Room Air Conditioners: Fiscal 1984, Japan

This paper describes the results of the third year of a three year program to establish calculational methods for energy efficiency ratios (EERs) for heat pump type room air conditioners. The algorithms developed in the first two years work for small heat pumps are first applied to a larger, single-speed heat pump. These same methods are then applied to inverter driven heat pumps and a calculational method for these systems is proposed. The paper also looks at the behavioral characteristics of thermostats used in Japan and at the low temperature test during heating that is adopted in the DOE C_d method.

5. Seasonal Efficiencies of Residential Heat Pump Air Conditioners with Inverter Driven Compressors, Hori, et al, Japan

This paper describes a study to determine experimentally the steady-state characteristics, cyclic effect, and frosting/defrosting effect of an inverter heat pump currently on the Japanese market and to compute its seasonal efficiency based on the local outdoor air temperature data. It was found that the annual performance factor (APF) of this heat pump is 15% higher than that of a conventional fixed speed heat pump. The APF of the inverter driven heat pump would be improved by another 2 to 6% if the cycling and frosting/defrosting losses are eliminated. It was determined that an additional parameter, such as an annual comfort factor, is needed to evaluate the performance of an inverter heat pump.

6. Report on HPC Visit to Japan, Halozan, Austria

A task force from the IEA Heat Pump Center (HPC) visited Japan from September 22 to October 3, 1986. The goals of the visit were to:

- improve contacts between the HPC and the members of MITI/AIST who are involved in heat pump development,
- establish personal contacts between the HPC and the Heat Pump Technology Center of Japan,
- explore the possibility of a Japanese scientist working for the HPC,
- gather information about inverter driven heat pumps and compressors, and
- develop contacts with companies operating heat pumps in industrial applications.

The visit was successful in accomplishing these purposes and this brief report summarizes some of the information obtained, lists the contacts made with representatives of Japanese utilities, heat pump manufacturers, contractors, engineering firms, and government organizations. Some heat pump performance information is included as are numerous photographs of heat pump installations visited.

7. Inverter Drive Heat Pumps: HPC Task Description

   This brief document outlines a project to be conducted by the IEA Heat Pump Center to evaluate the application of inverter driven heat pumps in Europe, North America, and Japan. Specific tasks are enumerated and a time schedule and required level of effort is attached.

8. Warmepumpenforschung in Graz, Halozan, Austria

9. Die thermodynamische Idee der Warmepumpe von S. Carnot bis P. von Rittinger, Gilli, Austria

10. Die Warmepumpentechniken im internationalen Vergleich: Moglichkeiten Und Voraussetunzgen fur eine breitere Markeinfuhrung, Halozan, Austria

11. Efficiency Degradation Due to Cycling and Refrigerant Migration of an Air-to-Water Heat Pump, Burtscher, et al, Austria

   The degradation of coefficient of performance (COP) for an air-to-water heat pump due to on/off cycling was evaluated through a series of experiments in which the cycle length and on-cycle length were varied at constant surrounding conditions. Measurements showed that the degradation of COP for this heat pump was not as severe as cycling losses for an air-to-air heat pump but was larger than losses for water-to-water systems measured at other institutes. The values of degradation of COP varied between 0.6 to 10.5% depending on the on-cycle time and the on-time.

12. First Set of Swiss Field Data, Conde, Switzerland

   This is a thorough description of the heat pump installation, data collection, and catalog heat pump performance for the first set of field data measurements contributed by Switzerland. It includes information on the defrost control system, nominal ratings of the evaporator and condenser, identification of the compressor and thermostatic expansion valve, and other general data on the heat pump. The installation in the home is described and the data format is given.

13. The Oak Ridge Heat Pump Models: II. An Annual Performance Factor/Loads Model for Residential Air-Source Heat Pumps, Rice, et al, United States

   This is the users manual for the ORNL APF/Loads model and contains a complete description of the algorithms used and the choices of correlations for computing frosting, defrosting, and cycling losses. It contains information on model validation, sample input and output data, and a description of the each input variable. Each subroutine and common block used in the program is described to assist users in adapting the model to their own specific purposes.

14. Description of U.S. Field Data, United States

15. Annual Energy Saving Effect of Capacity Modulated Air Conditioner Equipped with Inverter Driven Scroll Compressor, Senshu, Japan

This paper was presented at the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) in June 1985. It describes scroll type compressors and presents an analytical and experimental evaluation of the annual energy efficiency of a heating and cooling heat pump using an inverter driven scroll compressor. A heat pump using a constant speed scroll compressor was found to have an annual performance factor (APF) 8% higher than a heat pump using a reciprocating compressor of the same capacity. A capacity modulated heat pump with a scroll compressor had an APF 29% higher than a similar unit using a reciprocating compressor.

16. Inverter Control Systems in Residential Heat Pump Air Conditioner, Shima, Japan

This paper discusses the trends in the development of energy saving air conditioners in Japan and the objectives of developing inverter controlled air conditioners. It looks at the effects of employing an inverter on the air conditioner, on the refrigeration cycle, and air conditioner control with an inverter.

17. Laboratory Examination and Seasonal Analysis of Frosting and Defrosting for an Air-to-Air Heat Pump, Miller, United States

A nominal 9.7 kW capacity, air-to-air residential heat pump was instrumented and tested in environmental chambers in the laboratory. The coefficient of performance, system capacity, and component efficiencies were measured during steady-state and frosting-defrosting mode in the heating mode. Cumulative frosting and defrosting loss coefficients were calculated and empirical algorithms were developed for modeling of frosting and defrosting losses.

18. The Laboratory Evaluation of the Heating Mode Part-Load Operation of an Air-to-Air Heat Pump, Miller, United States

A split-system heat pump was instrumented and tested in the heating mode to gain a better understanding of the physical processes of the cycling phenomena that degrade heat pump coefficient of performance (COP) and capacity. The laboratory evaluation of the part-load COP and capacity of an air-to-air heat pump were conducted in a parametric study of heat pump on-time, off-time, and outdoor ambient temperature.

19. Steady-State Refrigerant Flow and Air Flow Control Experiments for a Continuously Variable Speed Air-to-Air Heat Pump, Miller, United States

A continuously variable-speed, air-to-air split-system residential heat pump of nominal 9.7 kW capacity was instrumented and tested in the laboratory. The coefficient of performance, capacity of the system, and component efficiencies were measured during steady-state heating and cooling mode operation.

20. The Effect of Void Fraction Correlation and Heat Flux Assumption on Refrigerant Charge Inventory Predictions, Rice, United States

Accurate computer predictions of heat pump performance are needed to design equipment with the maximum efficiency at off-design and transient operation. The refrigerant charge inventory is an important part of simulating performance under these conditions and this paper examines the effects of ten void fraction correlations and four heat flux assumptions on refrigerant charge inventory predictions. Comparisons between mass inventory predictions are made for condensers and evaporators over representative heat pump operating ranges of saturation temperature, mass quality, and mass flux. Implications of charge balancing, off-design and transient performance prediction, and unit reliability are discussed.

21. User's Manual and Tutorial of YUM, Afjei and Conde, Switzerland

This report is a comprehensive description of the program developed in Switzerland for estimating the seasonal performance factor of an electric driven, air-to-water heat pump. It describes the algorithms used for computing the frosting and defrosting losses and also the heating plant simulation model so that the heat pump can be simulated in combination with a load storage subsystem. All the necessary information is provided for using the YUM simulation code on a IBM PC or PC compatible personal computer.

22. Current and Future Advances in Small Heating-Only Heat Pump Systems, Halozan, Austria

The major worldwide markets for residential size heat pumps have been limited to the United States and Japan because of the need for heating and cooling in those countries. It has been difficult for heat pump systems to become established in regions like middle and northern Europe where heating only is required. This is because the high first costs of the units and installation cost of integrating the heat pump with a hydronic distribution system must be repaid through energy savings just during the heating season. This paper examines the opportunities for heat pumps to become economically attractive in heating only climates through the use of inverter drives because smaller capacity systems can be installed, reducing first costs, and also because of their higher operating efficiencies.

23. Thermodynamic Properties of Halocarbons, Ammonia, and Humid Air, Conde, Switzerland

Three computer programs are documented in this brief report. "HALOCARB" uses the modified Martin-Hou equation to compute the thermodynamic properties of refrigerants 11, 12, 13, 13B1, 14, 21, 22, 23, 113, 114, 500, and 502. "AMMONIA" calculates the properties of ammonia using the Rombusch equation. "PSYCHRO" computes the psychrometric properties of moist air. All three programs are written in Turbo-Pascal and operate interactively on IBM Personal Computers or PC compatible computers.

24. Second Set of Swiss Field Data, Conde, Switzerland

This is a thorough description of the heat pump installation, data collection, and catalog heat pump performance for the second set of field data measurements contributed by Switzerland. It includes information on the defrost control system, nominal ratings of the evaporator and condenser, identification of the compressor and thermostatic expansion valve, and other general data on the heat pump. The installation in the school is described and the data format is given.

25. Bivalent Heating Systems with Air-Source Heat Pumps: A Simulation Exercise, Conde, Switzerland

The computer simulation of heat pumps is required in many instances and at several levels of detail. A relatively simple simulation model is required for the analysis of the energy demand in buildings where heat pumps are normally integrated with a whole plant with other components. A simple mathematical simulation model is described in this paper for air-source heat pumps. It is a "black box" type of model but considers some of the state variables necessary in the simulation of the effects of frost and defrost. The model has been used by several participants in IEA Annex X to carry out some simulation studies. The objectives and results of those studies are summarized in this paper.

26. Validation of the Simulation Program "YUM" Against the Second Set of Swiss Field Data, Conde, Switzerland

This report presents the results of the first attempt to validate the Swiss heat pump simulation program YUM. Predicted values of thermal output, drive energy, run times, and monthly COPs are compared to measurements recorded in the second set of Swiss field data using both an hourly simulation and an algorithm using binned weather and loads data. The hourly simulation was found to predict the heating season COP to within 2.6%. It underpredicted both the thermal output and the drive energy. It is believed that the algorithm for computing the effects of frost on the evaporator is overly severe, resulting in underpredicting the thermal output, and that the estimate of drive energy is too low because on/off cycling is not accounted for.

27. <u>Description of the Computer Program Package WPHZ (Simulation of heat pump heating systems)</u>, Halozan, Austria.

The Austrian heat pump simulation program, WPHZ, is described in this document. It includes a discussion of the integrated building/-heat pump system modeled, each main program and subroutine used, and the structure of the input data. There is a listing of the computer program, sample input data, and results from a sample simulation.

ATTACHMENT 2

Implementing Agreement on Advanced Heat Pumps
Annex XII Computer Simulation Programs

Extension of Working Program for 1989

Proposal May 29, 1989

Annex XII was set up for a 18 months working period initially. It is therefore necessary now, to evaluate the work done so far and to compare the achievements with the goals set in the program of work.

The Operating Agent, Steve Fisher from ORNL, has prepared a report about the work done so far and its results. This work was concentrated on three different simulation models, developed at ORNL, Technical University of Graz, and ETH Zuerich, that are more or less able to simulate heat pump seasonal performance factors (SPF). The models and their particulars are being described in the report. A comparison of the models on basis of a common set of field data was not undertaken because of the different target application of the models. However material is being provided, showing results of individual model validations. In Italy a SPF model was not available, instead an air-to-air heat pump prototype was designed and tested, and the (steady state) experimental results were used to undertake a validation of the ORNL Heat Pump Design Model Mark III. A report about this work is presently being distributed among participants separately.

All work undertaken in the Annex so far was based on single speed heat pumps. The situation of variable speed heat pump SPF modeling has not been dealt with. The growing interest in these systems, mainly on the developers side, however, demands some activities in this particular field as well. It seems therefore worthwhile to undertake an analysis of the present status of SPF models with respect to their ability to simulate variable speed systems before concluding the Annex XII work. This work should be undertaken in a concerted effort and should be finished by the end of 1989.

Based on an initiative from the Italian participant, this proposal has been developed after having discussed the plan with other European participants, all of them having ongoing national programs in the field of variable speed systems and being very much interested in an analysis of the present situation of variable speed systems modeling. The results of this work to be undertaken in Annex XII shall then be used to identify the needs for further developments in this field in 1990.

On this background the work to be undertaken in 1989 in Annex XII should include the following main topics:

- investigate availability of variable speed models
- laboratory tests, steady state and SPF, of variable speed heat pumps and components
- comparison of test results with model calculations.
- evaluation of applicability and deficiencies of available models.

With the results of this work it will be possible to :

- identify further steps to support ongoing or planned national projects in the variable speed field
- develop a program for joint activities on variable speed heat pump systems to be started in 1990.

With the established working procedure of task sharing in this Annex, these topics are to be split up into individual tasks for each participant, organized, coordinated and concluded by the Operating Agent. Consequently, a proposal for splitting up these tasks among participants has been developed as presented in the listing below.

Austria:

- provide updated simulation program for variable speed heat pumps for hydronic systems
- undertake (laboratory) testing, steady state and SPF, and provide experimental data for variable speed air to air heat pumps (with the limitations of available testing installations)

Germany:

- undertake laboratory testing, steady state and SPF, and provide experimental data for variable speed hydronic heat pumps
- evaluate calculated and measured data for the tested systems

Italy:

- undertake laboratory testing and provide experimental data for various different variable speed compressors available on the market, including rolling piston and scroll compressors

Switzerland:

- undertake laboratory testing and provide experimental data of variable speed air to air heat pump (with limitations of existing testing installations), to be coordinated with testing in Austria
- provide comparative evaluation of calculated and measured data of air to air systems

USA:

- provide simulation program of variable speed air to air heat pump

All participants:

- provide 2000 US$ each for preparing final report on work 1989 as part of the final Annex XII report, and for organization and coordination of activities in 1989.

Operating Agent:

- organize and coordinate work in participating countries and inform participants on progress
- prepare final report on work performed in 1989
- develop proposal for work in 1990 in discussion with interested participants
- prepare and organize two technical working meetings, mid July and late fall 1989.