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USING DIGITAL COMPUTER SIMULATIONS FOR COMPRESSOR DESIGN

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INTRODUCTION

Within the last several years, complete simulations of refrigeration compressors have been developed (1,2,3). Because of the extensive information available in most compressor simulations, there are many potential uses still not apparent to the unacquainted users. Just a few of the uses are EER (Energy Efficiency Ratio) improvement, parts dimensional commonization, limits of performance due to tolerance variations, new design syntheses, extrapolations and interpolations of experimental data such as mass flow rate data, estimations of quantities that cannot be easily obtained experimentally, and fundamental data for other studies such as acoustics and stress analysis. It is believed that the number of designers that are aware of the uses of simulations is still rather small. Also they may not be aware of how criteria can be coupled with simulations so that a useful alternative to the classical experimental design approach is available.

The type of simulations that will be considered here may have the configuration shown in Figure 1. The figure outlines the major parts of many digital computer programs. The program contains a mathematical model, an integrating routine, and an initialization program. The mathematical model consists of nonlinear ordinary differential equations and algebraic equations some of which apply only over selected periods of time. The integrating routine acts as the center of activity of the program. Provision is made to print out numerical values of time dependent variables periodically such as valve motion and cylinder pressure or to print out integrated values such as mass flow rate and work of compression. Finally the initialization program is used to interpret the input data, to generate constants needed in the mathematical model, to plot selected time histories, and to restart the integrating procedure when sudden changes in the variables are encountered (e.g., when a valve contacts a stop).

In addition to the extensive information available from a compressor simulation, there are other reasons for using it. It has been shown in some performance improvement studies that a simulation routine is usually faster and can be executed with a cost saving of ten or twenty times over an experimental method. In the past two decades there has been a trend toward smaller higher speed compressors whose designs have not always followed previously accepted design rules of thumb. Thus designers often found themselves without intuition or a satisfactory model with which to study the problems. Simulations were developed to solve some of these problems. Simulations can sometimes replace the "art of compressor" design and allow designers to study design parameters that do not follow the older established procedures. Furthermore by using simulations greater precision of results is possible. This allows the designer to study trends without constant worry about statistical spreads that occur in experimental studies.

With regard to performance, the designer now must assign higher priority to the EER rating during the design procedure. This is due to the fact that product labeling seems imminent and air conditioner labeling is a virtual certainty. For the designer to produce the best EER for his designs within the size, weight, and cost constraints he needs powerful analytical tools such as computer simulation. Thus we expected that even more uses will be found for the simulation as the designer's experience with it grows and refinements he needs are added.

Since EER is receiving such considerable attention in industry we will arbitrarily choose it to illustrate the use of computer simulations in design. Thus optimum compressor design will be sought utilizing maximum EER as the criteria for best design. In many cases a manual procedure is used for adjusting the design parameters in which the designer is part of an iteration loop. Then because of the many design parameters to be varied, the designer must have procedures to guide him to his goals. Examples are shown where the simulation output is interpreted in such a way as to produce a better understanding of the influence of the different parameters. These techniques should be applicable to any compressor simulation provided it contains the necessary detail.

A DESIGN PROCEDURE

A design procedure that can be used is shown in Figure 2. It consists of a simulation, an interpretation/comparison of simulation results to design criteria, and a rational procedure for changing the design parameters so that the criteria ultimately can be met. It may be necessary to determine an optimum design for several operating conditions. This will allow the designer to see the sensitivity of the performance to parameter relationships for changes in operating conditions.

In setting the criteria used in the design procedure, the following suggestions may be helpful:

1. It is possible to use maximization of EER as a criteria. Also subordinate minimizations could be performed on work of compression, on energy losses through the discharge or suction ports, on leakage through the sealing surfaces, or on friction in the bearings.

2. The knowledge of theoretical limits will help the designer establish more feasible limits for a design problem. Based on polytropic compression processes the work per cycle can be calculated (4). Combining the work per cycle with an assumed one hundred percent volumetric efficiency an ideal EER can be calculated and can be used as an ideal upper limit on the EER. This calculated ideal limit cannot be achieved in real systems. Nevertheless, it is of value to a designer when he attempts to understand the differences between this ideal value and the value for the design under consideration.

3. A knowledge of practical limits is useful in order to properly allocate design effort. For example a designer should not try to expend his energy obtaining zero valve losses but instead try and obtain a reasonable value that past designs have achieved. In many cases these values will be quite close to the ideal limit.

4. A knowledge of legislated limits is important in setting criteria for design. For example, New York State has pending legislation on minimum EER's for air conditioners.

5. A knowledge of performance of competitive compressor designs can be useful in setting criteria. Different designs can serve as a useful backdrop for new design evaluations.

The interpretation phase of the design procedure partly consists of a comparison of the simulation output to the criteria established. For EER maximization this could be a comparison of the EER value to previous values perhaps visually observing where the maximum occurs on plots of the EER value versus the parameter being varied. Another part of the interpretation phase can be the analysis of the other performance variables that are used in calculating the EER.

An alternative approach can be taken for the interpretation phase using the differential of the logarithm of EER as given by the equation:

$$\mathrm{EER} = \frac{c \cdot m}{w}$$

where

m = lbm/hr.

w = total power input, watts

c = constant that represents the enthalpy change across the evaporator of a hypothetical system in which the compressor is used.

$$\frac{\Delta \mathrm{EER}}{\mathrm{EER}} \doteq \frac{\Delta m}{m} - \frac{\Delta w}{w}$$

Thus the percentage change in the EER is equal to the algebraic sum of the percentage change in the other variables, m and w.

Both m and w can be further expanded. This depends on the detail available in the simulation. A breakdown of w could contain

w = Motor Losses* + Friction Losses* + Power to Compress Gas*

*in watts

The friction loss can be broken down into different parts for the particular type of compressor. The power to compress the gas can be broken down to contain the following:

Power to Compress Gas = Suction valve loss + Discharge valve loss + Recompression power* + Leakage + Minimum power to gas.

*for Rotary Compressors

The minimum power to the gas can be calculated from the polytropic process.

The mass flow rate can be analyzed using the volumetric efficiency. Additional insight can be obtained by calculating the displacement per revolution, volume of discharge gas per revolution (obtained from the pressure time histories when cylinder pressure equals discharge pressure), clearance volume per revolution and the percent of compressed gas discharged (volume of discharged gas minus clearance volume/volume of discharge gas). Using these quantities the dependence of volumetric efficiency can be related to leakage or large clearance volumes.

Any rational procedure for design changes must consider only changes in parameters that are within the assumptions of the simulation. For example changes in the valve design would change the amount of overcompression which in turn may change the leakage by small amounts. Simulation may not predict the influences of these effects, in which case an additional analysis must be made to determine the effect on the total performance change.

The amount of change to be made in a parameter depends greatly on knowing the sensitivity of the performance index to that parameter and whether the performance index is near an optimum or near a constraint. Changes are easy to establish in a manual procedure when the designer is constantly interpreting the simulation results while changing a single parameter. Alternatively it is most difficult for a designer to establish changes when several parameters are to be varied at the same time. Some guidance should be evident from the examples, however much further progress needs to be made.

External constraints and additional criteria can be added to the design change phase in Figure 2. For example a typical constraint may represent the manufacturer's capability to hold tolerances and surface finishes. Others may relate to strengths and reliability of particular materials or configurations, conditions for quiet operation, design for good startup characteristics, and design for low-cost components.

EXAMPLES OF PERFORMANCE IMPROVEMENT

Results of performance improvement with respect to one variable are shown in Figure 3. The graphs show how particular functions related to performance vary with the particular parameter in this case discharge port diameter. They are taken from the work of Schult (5) on a single-lobe rotary vane compressor.

Graph 3b shows an optimum for IEER. IEER is calculated the same as EER except the power of compression is used in place of total power input.

Since IEER is proportional to mass flow rate divided by watts input, the graphs in Figure 3 can be analyzed to determine the cause for the optimum in IEER. The first quantity, mass flow rate, shown in Graph 3d has not changed appreciably. However, the indicated horsepower shown in Graph 3a has changed considerably showing it to be as the cause for the optimum. This can be further verified by noting that the IEER increased by approximately 10% (from its value corresponding to the minimum discharge port diameter shown) to its optimum while the indicated power decreased by approximately eight percent. Thus, about two percent of the increase remains to be attributed to an increase in flow rate. The minimum indicated horsepower further shows that there must be a counteracting influence acting on the indicated power making it increase beyond the optimum point since the discharge valve loss continues to decrease. If the discharge and suction valve losses are subtracted from the indicated horsepower, the remaining plot shows that the power to the gas is increasing to the right of the optimum. Since there is no reason for the minimum gas power to increase the difference must be due to larger recompression power required. This is a logical explanation since the larger port diameter to the right of the optimum creates larger clearance volume. It in turn will create a greater amount of recompression power. This could be verified by comparing the cylinder pressure time histories at the optimum and to the right of the optimum which show that the cylinder pressures are higher for those cases to the right of the optimum.

Another far more complex example is also taken from the study done by Schult. The preceding example showed a procedure for obtaining an optimum as a function of one geometric parameter while holding the others fixed. This procedure can be repeated for other parameters in the model. Fifteen parameters were used by Schult in the study. Optimums were obtained for variations with parameters characterizing the discharge porting system, suction porting system, sealing clearances, and swept volume. The interpretations and comparisons utilized other graphs for the other parameters like the ones in Figure 3 for the discharge port diameter.

Constraints can become important for some of the parameters. Schult held some fixed, since they were already at the limits of manufacturing or strength. Other parameters were found to have an optimum value when they were at their allowable limits. Parameters that controlled the swept volume had to be constrained so that the mass flow rate remained constant. This was necessary since compressors are usually sized for a certain capacity and usually used within a certain size motor.

Combining the local optima for each parameter into one design produced a new IEER which was then taken as an estimate of the overall optimum. The study then proceeded to ask the question, "is there a better set of parameter values which gives a better IEER?" In other words does a better overall optimum exist? If the effects of changing the parameters were independent of each other then the optimum IEER would not change. Schult showed this not to be the case since the improvements in IEER which he obtained this way were seventy percent of what was finally achieved. To achieve the final performance improvement a new search from the design combining the local optima was initiated.

Because of the boundary constraints on many of the parameters and because some parameters hardly influenced IEER, only four parameters remained for further optimization, after the search for the initial local optima. The first two of these considered (radius and height of cylinder) controlled the cylinder swept volume. Consequently Schult chose to vary them in such a way that the mass flow rate remained constant. It was interpreted from supporting graphs that the optimum ratio minimized leakage by determining the best arrangement of leakage path lengths. After determining new values for cylinder height and cylinder radius, the next step involved varying the two discharge porting parameters.

The net effect of determining the overall optimization in this way was to increase the performance by eight percent. This was only two percent more than the combination of initial local optima. However, these values could be considerably different when applied to other compressors.

Although it may be desirable to have a computational method which allows the computer to search for the overall optimum automatically there are advantages to the manual procedure just outlined. For example the manual interpretations between runs allowed a check of the validity of the model and input data, reduction in the number of simulation runs, and an understanding of what was important for the overall optimum. These understandings led to the conclusions that the optimum discharge and suction porting systems were largely dependent on the mass flow rate, that the volume could be shaped so as to reduce the seal leakage and that the volumetric efficiency usually rose as the flow rate increased. Obviously this knowledge has generality beyond the particular optimization study reported.

SUMMARY AND CONCLUSIONS

It has been shown that a digital computer simulation program can be used as a tool for optimum compressor design. A rational design procedure is described which allows the designer to pick optimum values of many compressor design parameters. The designer is required to interpret computer output during the optimization procedure outlined. Guidance for this interpretation is indicated with an example in which IEER is used as one of the performance indicies for optimum design. It is also shown that the computer output can provide the designer with an understanding of why the final design is optimum.

This example suggests the conclusion that a manual procedure be used for an approximate multiparameter optimization procedure provided an understanding of the component interaction is obtained. Through this smaller independent subsystem optima may be obtained which will lead to an overall system optimum.

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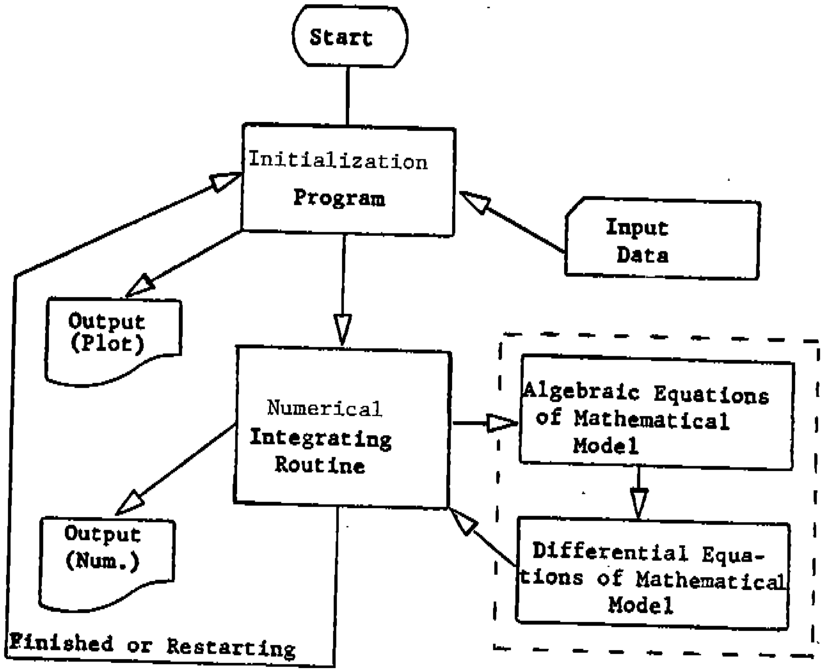


Figure 1. General Structure of a Compressor Simulation

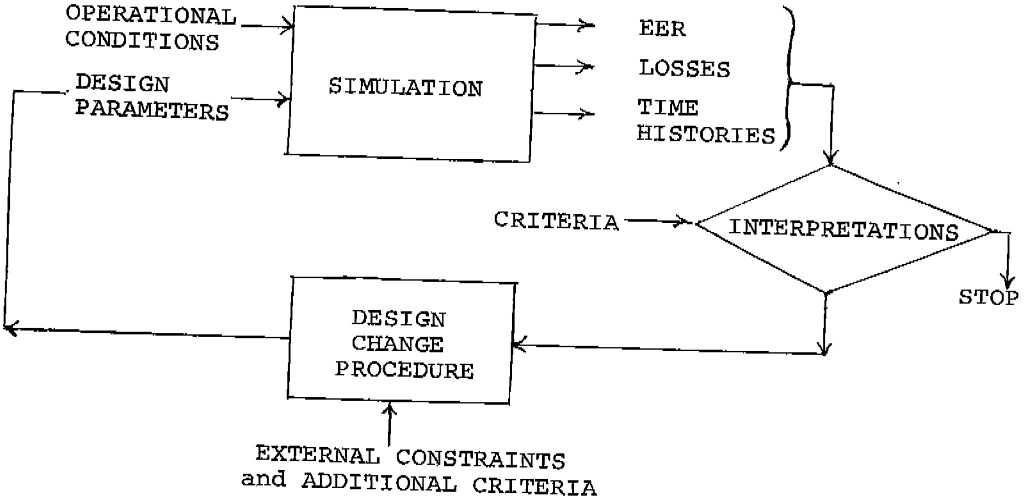
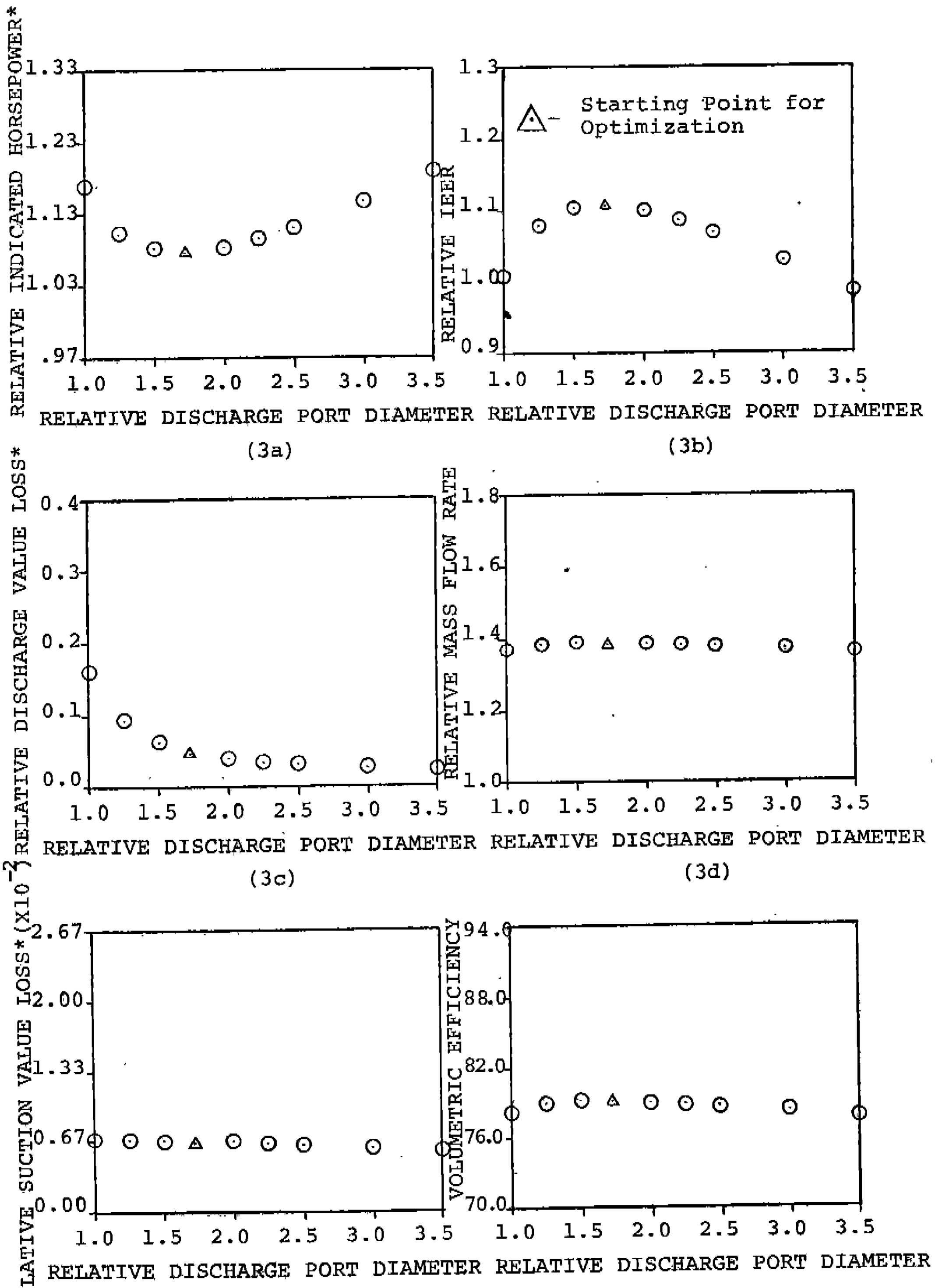


Figure 2. A Design Procedure for Using a Compressor Simulation



(3a) (3b)

(3c) (3d)

*All relative to the same base.

Figure 3. Relative Performance Indices Versus Relative Discharge Port Diameter (All Dimensionless)