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STOCHASTIC (PROBABILISTIC) SIMULATION FOR DESIGN AND ANALYSIS OF VAPOR COMPRESSION REFRIGERATION/HEAT PUMP SYSTEMS

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ABSTRACT

This paper describes the use of stochastic (probabilistic) simulation for design and analysis of vapor compression refrigeration/heat pump systems. Stochastic input variables: the condenser and the evaporator inlet temperatures, the degree of superheat at evaporator exit, the degree of subcool at condenser exit, the quality of the working fluid (Freon-12 or Ammonia) exiting the evaporator, the cooling load and the efficiency of the compressor are randomly introduced into the system model via their statistical distributions. Monte Carlo method is used for stochastic simulation. Output design variables: the daily operation cost, the compressor work load, the hot and the cold side coefficient of performances are characterized by their respective mean, standard deviation, normal distribution cumulative probability function and normal distribution probability density function.

INTRODUCTION

The expected performance of a refrigeration system is greatly influenced by the uncertainties involved in design parameters, design procedures and operational conditions. There are considerable uncertainties involved in process conditions, physical properties, and basic design correlations. Refrigeration systems are designed for a nominal set of conditions chosen to represent a presumed relatively conservative operational state of the system. In fact, it is highly unlikely that the system will ever operate under nominal design conditions. Condenser and evaporator inlet and outlet temperatures quality of the working fluid at the evaporator exit, compressor efficiency and cooling load all expected to vary during the operating life time of the refrigeration system. There are substantial inherent uncertainties in the physical properties, i.e., density, internal energy, enthalpy, entropy, heat capacities, etc. Also all of the correlations for the basic fluid flow and heat transfer mechanisms used to design system components i.e., condenser, evaporator, throttling valve, compressor, etc. are based on certain fundamental assumptions which are often violated in the real operating conditions. Prediction of the thermodynamic efficiency of the compressor is also very difficult.

Most of the models currently available for design and analysis of refrigeration system are deterministic in nature. In a deterministic model all the process inputs and design parameters are assumed to be constant. Therefore, the use of deterministic model for design, analysis and estimation of the performance of a refrigeration system could be very misleading. The result could be either a greatly overdesigned or severely underdesigned system.

A more sophisticated approach for process design and analysis is to use a probabilistic or stochastic model which takes into account the uncertainties in input design parameters. In a stochastic model output variables are characterized by their probability distribution.

STOCHASTIC SIMULATION

Stochastic model evolves through two main routes [1]: 1) Model derived by directly employing probabilistic concepts to small physical subdivision of the process, 2) Transformation of deterministic model into a stochastic model by introducing random variables into the system model. In the present study the latter approach is used. A computer
software based on stochastic model is developed to perform stochastic simulation for design and analysis of vapor compression refrigeration/heat pump systems [2]. This software is an extensive modification of a software based on deterministic model developed by Lawrence Livermore Laboratory [3]. In the developed software, the following stochastic input variables can be randomly introduced via their statistical distributions:

1) temperature of the condenser; ± % error
2) temperature of the evaporator; ± % error
3) degree of superheat of evaporator exit, ± % error
4) degree of subcool of condenser exit, ± % error
5) quality of freon-12 (or ammonia) exiting evaporator, ± % error
6) cooling load, ± % error
7) efficiency of compressor, ± % error

Since the uncertain quantities combine and interact in highly complex and nonlinear ways, the usual analytical methods could not be expected to yield useful results conveniently. Therefore, the Monte-Carlo simulation method is used. The Monte-Carlo Method consists of solving various problems of computational mathematics by means of construction of some random process for each such problem with the parameters of process equal to the required quantities of the problem. These quantities are then determined approximately by means of observations of the random processes and the computation of its statistical characteristics, which are approximately equal to the required parameters [4].

In the developed software it is assumed that the variations of the input design parameters, i.e., condenser and evaporator temperatures, degree superheat of evaporator exit, degree subcooled of condenser exit, quality of working fluid exit (freon-12 or ammonia), cooling load, compressor efficiency etc., are mostly concentrated around their nominal values and there is little known about their distribution. It is assumed that each variable is normally distributed. The Monte-Carlo method generates random numbers and provides a large number of successive solutions for the system. For each simulation a normal random number is generated for each of the above variables, and each parameter is assumed to be constant during the simulation once it has been generated. By having as many simulations as required, a set of values of the input variables is generated and this set is used to calculate deterministic outcomes of the system. Thus, a sample of the dependent variables is created from which the stochastic or probabilistic characteristics of the output variables are calculated.

In the present study the following output variables are calculated:

1) daily operation cost
2) work of compressor
3) coefficient of performance of hot side
4) coefficient of performance of cold side

Each of the above variables are characterized by their respective mean, standard deviation, normal distribution probability density function and normal distribution cumulative probability function.

Stochastic simulation is performed for a simple vapor compression refrigeration system. The schematic diagram of the system is given in Figure 1. Input design parameters are given below:

1) Working Fluid: Freon-12
2) Number of Simulations: 100
3) Input design specification:
   a) Temperature of the evaporator, % error -40°C ± 10%
   b) Temperature of the condenser, % error 40°C ± 10%
   c) Degree of superheat at the evaporator exit, % error 10°C ± 10%
   d) Degree of subcool at the condenser exit, % error 10°C ± 10%
e) Quality of freon-12 exiting the evaporator, % error 100% ± 10%
f) Cooling load, % error 25 tons ± 10%
g) Efficiency of the compression, % error 70% ± 10%

SIMULATION RESULTS AND ANALYSIS

Results of the stochastic simulation are given in Figures 2 through 9 and are summarized in Table 1.

Analysis of the results shows that due to the uncertainties in the input parameters, for a 95% confidence interval, the daily operation cost of the refrigeration system varies from $11.97 to $52.50 and work of the compressor varies from 14.23 KW to 62.53 KW. Hot and cold side coefficient of performance (COP) varies from 1.88 to 5.18 and 0.88 to 4.18 respectively.

Also by analyzing Figures 2 through 9 we can predict the performance of the system from a probabilistic viewpoint. Figures 2, 4, 6 and 8 can be used to estimate the probability of achieving a specific operation cost, compressor work, hot side COP and cold side COP respectively. For example: the probability that the daily operating cost would be $40.5 (or less) is 78%; the probability that the work of the compressor would vary from 28.5 KW to 48.2 KW is 58%; there is only a 50% probability that cold side COP of the system would be about 2.5 (or less); the probability of achieving hot side COP between 4 and 5 is only 13%, etc. Similarly, Figures 3, 5, 7 and 9 can be used to estimate the relative frequency of achieving a specific operation cost, compressor work, hot side COP and cold side COP respectively.
The Daily Operation Cost, $ 

**Figure 2. Cumulative Probability of Variation of the Daily Operation Cost.**

**Figure 3. Normal Distribution of Variation of the Daily Operation Cost.**
**Figure 4.** Cumulative Probability of Variation of the Compressor Work.

**Figure 5.** Normal Distribution of Variation of the Compressor Work.
**Figure 6.** Cumulative probability of variation of the coefficient of performance (Hot Side).

**Figure 7.** Normal distribution of variation of the coefficient of performance (Hot Side).
Figure 8. Cumulative Probability of Variation of the Coefficient of Performance (Cold Side).

Figure 9. Normal Distribution of Variation of the Coefficient of Performance (Cold Side).
### Table 1

RESULTS OF THE STOCHASTIC SIMULATION

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th># OF SIMULATION</th>
<th>MEAN</th>
<th>STANDARD DEVIATION</th>
<th>95% CONFIDENCE INTERNAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>*The daily operations cost, $</td>
<td>100</td>
<td>32.24</td>
<td>10.34</td>
<td>11.97 to 52.5</td>
</tr>
<tr>
<td>work of compressor, KW</td>
<td>100</td>
<td>38.38</td>
<td>12.32</td>
<td>14.23 to 62.53</td>
</tr>
<tr>
<td>COP Hot Side</td>
<td>100</td>
<td>3.53</td>
<td>0.84</td>
<td>1.88 to 5.18</td>
</tr>
<tr>
<td>COP Cold Side</td>
<td>100</td>
<td>2.53</td>
<td>0.84</td>
<td>0.88 to 4.18</td>
</tr>
</tbody>
</table>

* The operations cost, based on a 50% duty cycle and 0.07 $/KW-hr.

### Conclusions

Stochastic simulation for design and analysis of refrigeration system is much more practical than a deterministic one. Using the stochastic simulation the effect of uncertainties in the input design parameters upon the performance of a refrigeration system can be analyzed from a probabilistic viewpoint. By analyzing the sensitivity of the output variables to the uncertainties in the input, the most critical component of the system can be identified; if this component can be closely controlled, the performance of the system will significantly improve.

### References