PERGAMON

Energy Conversion & Management 40 (1999) 1651–1660

ENERGY
CONVERSION &
MANAGEMENT

www.elsevier.com/locate/enconman

Technico-economic simulation and optimization of a compression refrigerating machine

Lavinia Grosu*, Riad Benelmir, Michel Feidt

LEMTA UMR CNRS 7563, 2 avenue de la Forêt de Haye, 54516, Vandoeuvre-Lès-Nancy Cedex, France

Abstract

This study is among the several works conducted by the authors with regard to technico-economic optimization of refrigerating machines. The most difficult part is the gathering of technico-economical data and the development of cost correlations. The tool presented in this work will be used for an optimization based on irreversibilities and cost minimization, since irreversibilities have a direct impact on the operating cost. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Optimization is a process that consists in defining conditions that will lead to the maximum or the minimum of a function. For a plant, optimization means generally a process of search of a design point of the system for an optimal performance. More particularly, the optimal system is the system that will result directly or indirectly in a lowest total cost and that will have in the same time an acceptable impact on the environment.

As will be shown in the following simulation codes are developed in two steps. In the first part we choose the most favourable configuration of the refrigerating machine for a given compressor type. Then, we characterize the thermodynamic states of the cycle. For that purpose, it is necessary to set some parameters required of the machine. Hence, the total investment cost of the refrigerating machine is determined.

---

* Corresponding author.

PII: S0196-8904(99)00058-8

Nomenclature

cp(,)	matrix containing compressors technico-economic data
ev(,)	matrix containing evaporators technico-economic data
cd(,)	matrix containing condensers technico-economic data
i_{cp}	compressor type
i_{cd}	condenser type
i_{ev}	evaporator type
P_{cp}	compressor electrical power [W]
$P_{\mathrm{i_{cp}}}$	indicated power of the compressor [W]
P_{ev}	heat transfer rate at the evaporator [W]
P_{cd}	heat transfer rate at the condenser [W]
$\dot{m}_{\mathrm{ff}}$	refrigerant mass flow rate [kg/s]
$\dot{V}_{\mathrm{cp}}$	refrigerant real volumetric flow rate at the compressor [m^3/s]
$\dot{V}_{\mathrm{cpth}}$	refrigerant theoretical volumetric flow rate at the compressor [m^3/s]
$\dot{V}_{\mathrm{fc_{ev}}}$	heating fluid volumetric flow rate [m^3/h]
$\dot{V}_{\mathrm{fc_{cd}}}$	cooling fluid volumetric flow rate [m^3/h]
$T_{\mathrm{fc_{ev}}}$	outlet temp'rature of the heating fluid [°C]
$T_{\mathrm{fc_{cd}}}$	inlet temperature of the cooling fluid [°C]
T_{asp}	inlet temperature at the compressor [°C]
DT_{ev}	evaporator temperature pinch
DT_{cd}	condenser temperature pinch
$DT_{\mathrm{fc_{ev}}}$	temperature variation of the heating fluid
$DT_{\mathrm{fc_{cd}}}$	temperature variation of the cooling fluid
T_{ev}	evaporating temperature [°C]
T_{cd}	condensing temperature [°C]
$D\mathrm{h}_{\mathrm{ev}}$	enthalpy variation of the heating fluid [J/kgK]
$D\mathrm{h}_{\mathrm{cp}}$	enthalpy variation of the cooling fluid [J/kgK]
cyl	compressor cubic capacity [cm^3]
rpm	compression speed [min^{-1}]
ci_{cp}	compressor investment cost [FF]
ci_{cd}	condenser investment cost [FF]
ci_{ev}	evaporator investment cost [FF]
ci_{t}	total investment cost [FF]
c_{t}	total cost [FF]
c_{el}	electricity unit cost [FF/kWh]
N_{h}	operating hours
c_{f}	operating cost [FF]
c_{m}	maintenance cost [FF]
$\mathrm{cp}_{\mathrm{ev}}$	heating fluid specific heat
$\mathrm{cp}_{\mathrm{cd}}$	cooling fluid specific heat
$\mathrm{ci}_{\mathrm{opt}}$	optimal total cost

COP coefficient of performance
COP_{th} Carnot coefficient of performance

Greek Symbols
$\eta\tau$ exergetic efficiency
ρ_{ev} heating fluid density
ρ_{cd} cooling fluid density
$\eta_{v_{cp}}$ compressor volumetric efficiency

In the second step, by means of the cost correlations it is possible to estimate, with a very good approximation, the total cost of the machine. Therefore, we present an evaluation of investment costs for continuous and not only discrete key parameters.

In this study we present a numerical optimization example for the case of a simple compressor refrigerating machine.

2. Technico-economic simulation

2.1. First part of the simulation code

The technico-economic data extracted from manufacturers catalogues for each component of a refrigerating machine is presented as following example see Tables 1-3:

2.2. Input data

- nature of refrigerating (R22), heating fluid (air) and cooling fluid (water)
- technico-economic data
- evaporating temperature
- condensing temperature

Table 1
Data for hermetic positive displacement compressors (feed voltage: 200–240 V)

Type	cyl	P_{ev}	P_{cp}	ci_{cp}
1	10.3	835	475	1390
2	12.9	1070	553	1420
3	15.3	1325	612	2140
4	20.6	1670	950	2350
5	25.8	2140	1107	2470
6	30.6	2650	1225	2540

Table 2
Data for pulsed air finned tubes evaporators

Type	P_{ev}	$V_{fc_{ev}}$	ci_{ev}
1	850	685	1145
2	1100	665	1215
3	1700	1370	1823
4	2200	1330	1926
5	2600	2055	2492
6	3300	1995	2643
7	4300	2660	3505
8	5500	3325	4417

- inlet temperature at the compressor
- compressor speed

The technico-economic and thermodynamic calculation algorithms are shown in Figs. 1 and 3, respectively.

For a given type of compressor, i_{cp}, the thermodynamic calculation code read the following compressor data: the consumed electrical power at the compressor, P_{cp}, the corresponding refrigerating capacity, P_{ev}, the cubic capacity, cyl, and the investment cost, ci_{cp}.

Therefore, through the knowledge of the refrigerating capacity, the evaporator type, i_{ev}, as well as the investment cost, ci_{ev}, are defined from the evaporator data.

Finally, by means of an energy balance for the refrigerating cycle, the condenser heat transfer rate, P_{cd}, is defined and allows the determination of the condenser type, i_{cd}, and the investment cost, ci_{cd}, from the condenser data.

Hence, the total investment cost of the refrigerating machine is calculated. We neglect the expansion valve investment cost because it is much smaller than other components cost. Study for a cogeneration engine allows to estimate the maintenance cost at 25% of the investment cost but this part of the cost is very dependent on the local administrative and contractual network. The operating cost is a function of the compressor consumed electrical power and the eletricity unit cost which is assumed invariant. The total cost of the machine does not take into account the rate of actualization and the payback period [1].

In Fig. 2 we draw the thermodynamic cycle in order to indicate the states numbering.

Text in bold character is used for the known parameters. By "state (i)" we understand

Table 3
Data for concentric tubes water condensers

Type	P_{cd}	$V_{fc_{cd}}$	ci_{ev}
1	3500	0.6	1222
2	5000	0.6	1453
3	9000	1.0	1926
4	14000	1.4	3103
5	20000	2.0	4931

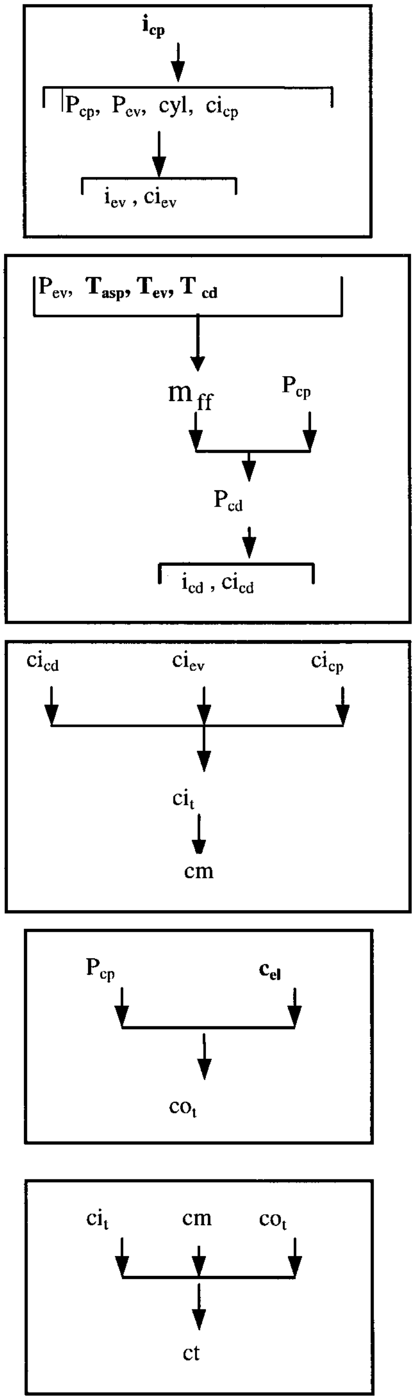

Fig. 1. Algorithm for the technico-economic calculations.

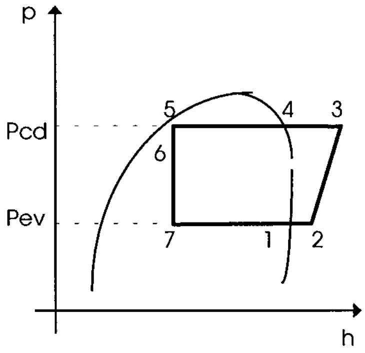

Fig. 2. Thermodynamic cycle.

thermodynamic characteristics of the refrigerating fluid at the point «*i*» of the thermodynamic cycle.

2.3. Results

This simulation software allows for a given type of compressor, along with parameters defined above, to end up with the corresponding type of evaporator and condenser, as well as the determination of the cycle thermodynamic states and the total investment cost, see Table 4.

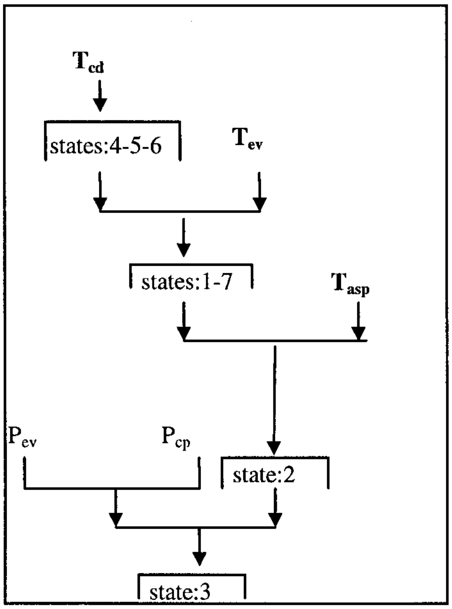

Fig. 3. Algorithm for thermodynamic calculations.

Table 4
Results of the technico-economic simulation

Point	T [°C]	P [bars]	h [kJ/kg]	s [kJ/kgK]
1	−6	4.07	281.29	1.09
2	32	4.07	308.02	1.18
3	131	17.28	372.08	1.23
4	45	17.28	295.59	1.02
5	45	17.28	134.67	0.517
6	45	17.28	134.67	0.517
7	−6	4.07	134.37	0.542
P_{cp}	612			
P_{ev}	1325			
P_{cd}	1814			
$\dot{m}_{ff}$	7.6e−3			
$\eta_{r_{cp}}$	0.7			
ci_t	4577			

This simulation code allows one to estimate the machine operating conditions and its total cost based on a a given compressor type. It is rather restrictive in use but very practical for a quick evaluation for a known operating range.

2.4. Remarks

1. Calculations are conducted with a compressor global efficiency about 80%.
2. The refrigerant temperature at the discharge of the compressor is approximately 110°C when the internal cooling within the compressor is taken into account.
3. No condenser subcooling.
4. In this study we neglect the investment cost of insignificant and auxiliary components as the expansion valve, the oil separator, the surge drum, the refrigerant drier.

2.5. Second part of the simulation code

This second part uses the first part in order to assess the problem based this time on a given

- cold source temperature,
- hot sink temperature,
- and refrigerating capacity

with constraints on the following variables:

- evaporator temperature pinch
- condenser temperature pinch
- compressor suction temperature

In this second part of the simulation code the investment cost is not extracted from the tabulated data corresponding to the component type but evaluated by means of correlations developed in a previous work by the authors [2] using the tabulated data. This means of calculation allows the evaluation of investment costs for continuous and not only discrete key parameters.

Investment cost of the compressor:

$$ci_{cp} = 9.21.10^{-8}.\mathrm{cyl}^{4.85}.P_{ev}^{3.3}.P_{cp}^{2}$$

with:

$$10.3<\mathrm{cyl}<30.6 \quad (\mathrm{cm}^3)$$

$$835<P_{ev}<2650 \quad (\mathrm{W})$$

$$475<P_{cp}<1225 \quad (\mathrm{W})$$

Investment cost of the condenser:

$$ci_{cd} = 2.4.10^{5}.P_{cd}^{-0.53}.V_{fc_{cd}}^{1.96}$$

with:

$$3500<P_{cd}<20000 \quad (\mathrm{W})$$

$$0.6<\dot{V}_{fc_{cd}}<2 \quad \left(\mathrm{m}^3/\mathrm{h}\right)$$

Investment cost of the evaporator:

$$ci_{ev} = 2.94.P_{ev}^{0.44}.\dot{V}_{fc_{ev}}^{0.42}$$

with:

$$850<P_{ev}<5500 \quad (\mathrm{W})$$

$$685<\dot{V}_{fc_{ev}}<3325 \quad \left(\mathrm{m}^3/\mathrm{h}\right)$$

3. Technico-economic optimization

The objective function of the optimization problem is the total cost of the refrigerating machine defined earlier [3]:

$$c_t = ci_t + co_t + c_m$$

with:

Table 5
Optimisation results

DT_{ev}	7
DT_{cd}	8.4
T_{asp}	27
$c_{\mathrm{t_{opt}}}$	12670
COP	2.04
$\mathrm{COP_{th}}$	5.54
η_{τ}	0.37

$$c_{\mathrm{m}} = 0.25^{*} c\mathrm{i}_{\mathrm{t}}$$

and:

$$co_{\mathrm{t}} = c_{\mathrm{el}}^{*}(P_{\mathrm{cp}}/1000)^{*} N_{\mathrm{h}}$$

where:

$$c_{\mathrm{el}} = 0.56\ \mathrm{F/kWh\ and}\ N_{\mathrm{h}} = 8000\ \mathrm{h}$$

3.1. The fixed parameters

- the refrigerant (R22), the cold source (air) and the hot sink (water)
- the cold source temperature (outlet temperature of the evaporator fluid)
- the inlet temperature of the cooling fluid at the condenser (hot sink)
- the refrigerating capacity

3.2. The constraints

- on the evaporator temperature pinch (less than 8 K)
- on the temperature variation of the cold fluid at the evaporator (less than 5 K)
- on the condenser temperature pinch (less than 10 K)
- on the compressor suction temperature (less than 32°C)

Most of the values of the constraints above are obtained from technical brochures given by manufacturers.

The optimization search is conducted by means of an optimization tool developed by Lasdon and Waren [4]. It solves nonlinear problems by the Generalized Reduced Gradient Methods. A good choice of the initial point is important for reaching an optimum.

3.3. Results

We give for example the results of the optimization for the following fixed parameters:

$$P_{\mathrm{ev}} = 2500\ \mathrm{W}$$

Table 6
Exergetic efficiency variation

$T_{\mathrm{fc}_{\mathrm{cd}}}$	T_{cd}	$\mathrm{COP}_{\mathrm{th}}$	COP	η_{τ}
20	28.4	8.02	2.04	25.4
25	33.4	6.98	2.04	29.2
30	38.4	6.18	2.04	33.01
35	43.4	5.54	2.04	36.82

$$T_{\mathrm{fc}_{\mathrm{ev}}} = 2C$$

$$T_{\mathrm{fc}_{\mathrm{cd}}} = 35C$$

Table 5 present the results of the optimization.

Of course, variation of some parameters allows the variation of the point optimum. If we choose other percentages for the maintenance cost we obtain that the increase of this percentage implies the increase of the total cost.

We can study the influence of the inlet temperature of the cooling fluid on the exergetic efficiency. The results are presented in the following Table 6:

4. Conclusions

This study is the first step of an optimization of a refrigerating machine. It will be used for an optimization based on irreversibilities and cost minimization, since irreversibilities have a direct impact on the operating cost [5].

One of the most complicated starting points for the model was obtaining the technico-economics data and especially coupling the different components of the machine.

It is very important to establish a correct cost correlations with a good approximation for a given interval of parameters.

In the follow-up of this work one introduces parameters which involve internal and external exergetic losses. Therefore, the optimization of refrigerating machine will take into account this exergetic loss.

References

[1] Chatelain C, Ducrocq J-C, Mignard B, Coeytaux M. Optimisation technico-economique des processus énergétiques. Technique de l'Ingénieur, Génie énergétique 1996;B1282:1–24.

[2] Grosu L, Belelmir R, Feidt M 1997 Contribution a l'étude exergo-économique des systèmes de refrigération. BIRAC'97, Bucharest 1997, communication invitée.

[3] Benelmir R, Feidt M. Thermoeconomics and finite size thermodynamics for the optimization of heat pump. In: ECOS'96, Stockholm, Proceedings, 1996. p. 99–103.

[4] Lasdon LS, Waren AD 1986 GRG2 User's Guide. Department of General Business, School of Business Administration, University of Texas at Austin, Austin, Texas 78712, USA.

[5] Benelmir R, Goulhiane A. Comparaison de deux approches d'optimisation. Application à une thermopompe. Rev Gén Therm 1996.