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Petersen, P.M; Qvale, Einar Bjørn

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CONTROL AND OPTIMIZATION OF THE REFRIGERATION PLANT IN A BREWERY

P.M.Petersen and B.Qvale

Laboratory for Energetics

The Technical University of Denmark

ABSTRACT

The design and operation of a refrigeration plant in a brewery has been studied. The plant has been evaluated by using mathematical models of the components to simulate responses to real-life load variations.

The study shows, that the effiency and economy for the actual refrigeration plant could be improved significantly by a combination of three different approaches: design optimization, improved operation strategy and load management.

The improvements obtainable by each approach and by combinations of these are reported.
A reduction of primary fuel consumption of 15 % is obtainable ideally, while a realistic practical goal is 10 %.

INTRODUCTION

Industrial energy systems are often characterized by complex designs and highly fluctuating loads, caused by numerous consumers and subsystems. These characteristics make analysis and overall optimization of the design and operation of an complex energy system an extensive and time consuming work. A plant is described by a large number of design variables and should be evaluated in many load points in order to determine an absolute best economy for a plant.
Furthermore, an overall optimization of a complex energy system is not well defined from a mathematical point of view. Often basically different system designs must be compared. This problem is discrete and non-linear, which turns an overall optimization into a combinatorial problem rather than a continuous mathematical problem.

However, as energy prices rose during the nineteenseventies, a considerable effort was invested in reducing the consumption of primary fuel and in developing improved design methods for energy-intensive industries. Although the fuel prices have decreased during the eighties, this effort has been continued. With an increased emphasis on environmental issues during the next decades, these activities will increase in importance.

Still, not many studies of optimization methods and applications of these have been reported. Energy conversion plants have been studied [1]-[3], but the results can not be compared because of the completely different methods used and because of the much different energy demands, economics, environmental conditions etc. One second law study [1] shows, that the optimum distribution of the heat-transfer area in evaporator and condenser for conventionel heat pumps is independent of temperatures, Carnot efficiency and heat-transfer coefficients, but does not attempt to find the optimal distribution for various system configurations. Another one, [2], gives some "rules of thumb" for the placement of heat pumps relative to heat-exchanger networks, but does not consider the optimization of the heat pump itself.

In general, optimization studies of the above type usually only consider single load points. But part-load operation is the most frequent operating mode in many energy systems. As important operating conditions change hourly, daily, and annually, realistic load series should be used. Even if most of the fuel consumption occurs at high loads, poor part load operation will significantly impair the total economy of a plant.
Therefore, for the evaluation of complex energy systems, simulation techniques may represent the most useful tool. Using mathematical descriptions of performance curves for important components in a system and real-life load series, different designs and operational strategies can be evaluated and compared. Widely different system configurations and operational strategies can be tested and a best overall design and performance can be obtained. But it is difficult to generalize the results. At best, the results contribute to the pool of experiences resulting from such simulation studies. The present work belongs to this last type of investigations.

THE REFRIGERATION PLANT

The refrigeration plant studied is operating at a brewery near Copenhagen, Denmark. The plant is using ammonia as refrigerant and delivers saturated ammonia at high pressure for cooling purposes for the entire brewery, e.g. in the brewing processes, fermentation tanks, storage rooms etc. The ammonia is evaporated locally at two pressures, corresponding to cooling needs at -6°C and -10°C.

The condensers are common to the two systems ope-
rated at these two evaporator pressures. In total,
an amount of 45 tons of ammonia is circulating in
the refrigerant system. The power consumed by
compressors and pumps is 3700 MWh/year.

The needs for cooling in each system varies with
the operation of the principal brewing processes,
and the loads vary widely througout the week and
the year. The cooling loads in each utility system
have been measured every thirty second during half
a year [4] and the data have been averaged over two
hours. The load profiles in the two systems for a
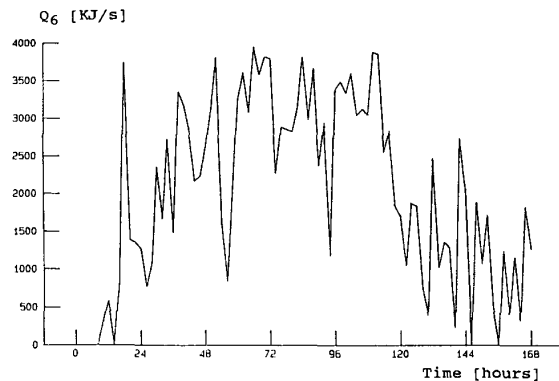week in August are shown in figure 1a and 1b.

Q_6 [KJ/s]

Figure 1a. Demand variations at -6°C during a
        week in August.
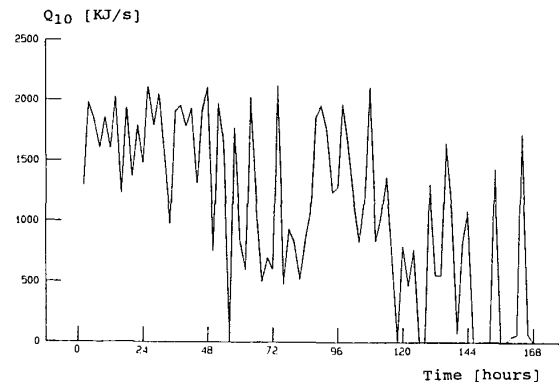
Q_{10} [KJ/s]

Figure 1b. Demand variations at -10°C during a
        week in August.

During winter operation (February), the loads are
approximately halved compared to the loads in
August.

To insure a satisfactory operation and effiency at
all loads, the refrigeration plant is designed with
a number of condensers (9), high-efficiency screw
compressors (3) and low-efficiency reciprocating
compressors (4), and a number of pumps (3) and
pipes (2) for pumping sea-water.

The management of these components is handled by a
control system, where simple strategies for how to
operate and combine compressors, condensers and
pumps as the load varies are implemented. The
principal concerns are the efficiency of the screw
compressors and the part-load performance of the
reciprocating compressors. As the thermal capacity
of the utility systems is small relative to the
loads, part load is the most common operating mode
for the compressors.
The plant also contains other components as
receivers, buffers and valves [4].

System model

A mathematical simulation model has been developed
in order to evaluate the system performance and to
investigate alternative system designs and manage-
ment strategies. The real load-series have been in-
ferred from the production (KJ/s) of the compres-
sors. The total system can therefore be described
without considering the detailed design of the
utility systems and without considering the dyna-
mics of the distribution system. A quasi-static
description of compressors, pumps and condensers
will then be sufficient to simulate and evaluate
different system designs and operating strategies.

The simulation model contains mathematical descrip-
tions of each of the main components in the refri-
geration plant. These descriptions represent curve
fits of empirical data [4]. These performances are
given at part-load and full-load operation as func-
tion of the most important operating condition of
the plant, the sea-water temperature.

Simulated performance

The mathematical model is used to simulate the sys-
tem performance. The components to be in service in
each load situation are selected by the same crite-
ria as by the present control system. An example of
the resulting coefficient of performance (COP) for
the total refrigeration plant as a function of the
load in the -6°C system for two values of the load
in the -10°C system is shown in figure 2.

The sudden changes in the curves are caused by
varying selection of compressors, condensers and
sea-water pumps with changing loads in the -6°C
system. It is seen, that the COP will vary signi-
ficantly when using the present operating strategy
and that the best efficiency is obtained at a load
of approximately 1500 KJ/s, corresponding to full-
load operation of one screw compressor. When the
reciprocating compressors are used and at part-
load, the COP of the system is lower. In addition,
several COP values are low because of a poor
matching between the power consumption for the sea-
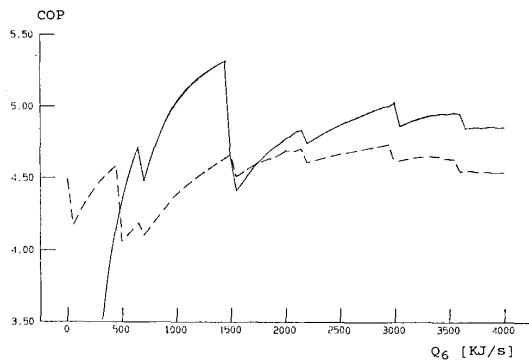water system and the compressors.

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COP

Figure 2. COP for the refrigeration plant as the
load increases in the -6°C system, su-
bject to sea-water conditions in August.
(———) : Q_{10} =   0 KJ/s.
(- - - -) : Q_{10} = 1000 KJ/s.

A load profile has been simulated for a week in
August, and the COP variation during the week is
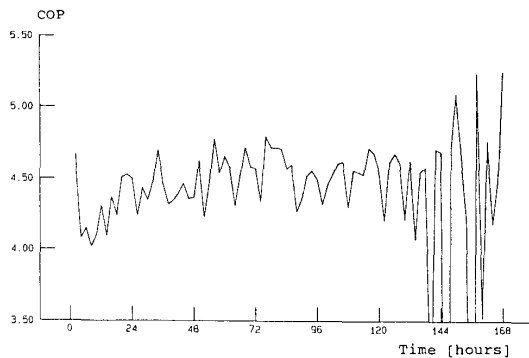shown in figure 3.

COP

Figure 3. COP variation for the refrigeration
plant during a week in August.

It is seen that the system COP shows large varia-
tions during the week. This is mainly explained by
the influence of the load variations in the -10°C
system (the lower evaporation temperature in this
system results in a lower COP). Secondly, the COP
fluctuates because of changes in selection of com-
ponents as seen in figure 2. Several of the lower
values are caused by extreme part-load operation of
the compressors.
The weekly power consumption in August is found to
be 119.2 MWh. In February, the weekly power con-
sumption is found to be 43.1 MWh.

MANAGEMENT AND OPTIMIZATION OF THE PLANT

The results in figures 2 and 3 illustrate how the
fluctuating loads lead to a reduced overall effi-
ciency of the refrigeration plant. Compressors
must often be operated at part load and it is often
necessary to operate several reciprocating compres-
sors to meet the required cooling. In both situa-
tions, the overall efficiency is reduced.
The fluctuating loads, furthermore, make it imprac-
tical to design a plant with a highest possible
efficiency at all loads. This would require an
inordinately large number of components. In the
existing refrigeration plant, the sea-water system
and the compressors can only be operated together
at their best efficiency in narrow load intervals,
because of the required accurate control of the
sea-water flow that is necessary in order to mini-
mize the condenser temperature in each load situa-
tion. In order to obtain the highest efficiency at
all loads, it would be necessary with several
different sea-water flows and an advanced strategy
to manage these. The strategy and system required
to achieve an absolute best performance would be
too complicated and expensive in most contexts.

The idealized operation of the plant will now be
considered in order to establish the reasonable
targets for an improved design and operation.

Targets for an improved design and operation

The targets for an improved design and operation of
the refrigeration plant can be established by con-
sidering the average loads in each utility system
during the week. This would be the ideal load
situation for the plant, and the plant could be de-
signed with a maximum efficiency corresponding to
this operation.
When the refrigerant plant is optimized for this
constant operation, the weekly power consumption
would be 104.5 MWh in August. In February, the
weekly power consumption would be 34.1 MWh. Com-
pared to the actual consumption, the max. obtain-
able reductions are 12.3 % in August and 20.9 % in
February. The annual power consumption would be
reduced by 15.6 %.

Optimal design and management of the plant

The weekly load profile has been simulated for
various designs of the plant and for various stra-
tegies for how to manage the components.
The design optimization is performed by evaluating
different existing sizes of the screw compressors
and the sea-water pumps, all with performance
curves corresponding to the present components. To
insure a proper operation at all loads, both
summer and winter weeks have been simulated.
For the operation of the components, the present
(simple) strategy is compared to an advanced
strategy. During the present operation of the
plant, two screw compressors are kept constantly
on alert in the -6°C system and one is kept on
alert in the -10°C system. With the advanced stra-

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		WEEKLY POWER CONSUMPTION MWh.	WEEKLY NUMBER OF ON/OFF-OPERATIONS		
			screw compressors	reciprocating compressors	sea-water pumps
PRESENT DESIGN simple management:	August	119.2	94	138	14
	February	43.1	94	70	32
advanced management:	August	115.9	268	228	676
	February	40.9	364	114	170
DESIGN OPTIMIZED FOR SIMPLE MANAGEMENT	August	115.0	94	140	14
	February	41.0	94	70	32
DESIGN OPTIMIZED FOR ADVANCED MANAGEMENT	August	111.9	666	288	74
	February	37.5	208	92	54

Table 1.   Weekly power consumption and weekly number of ON/OFF-operations for various optimized designs and management strategies.

tegy, the best combinations of compressors, pumps and condensers are selected in each load situation, and the screw compressors are allowed to alternate between the two utility systems.

The results are shown in table 1, where the weekly power consumption and number of ON/OFF-operations of the components are listed. In order to obtain the practical number of ON/OFF-operations, the plant has been simulated in steps of 15 minutes assuming linear changes in the loads between the recorded 2 hour loads.

It is seen, that for the existing plant, an absolute best management of the components in each load situation leads to a modest reduction of the power consumption. In total, this management of the components leads to an annual saving of 3.7 %.

However, the weekly number of ON/OFF-operations of the screw compressors is more than doubled relative to the present numbers, which is a critical increase. Frequent ON/OFF-operations lead to stresses in the components and hereby to a reduced reliability of the plant. Especially the sea-water pumps must be started and stopped frequently in order to keep the condenser temperature low.

If the design of a plant that is operated with the simple (present) management strategy is optimized, the weekly power consumption would be 115.0 MWh in August and 41.0 MWh in February. In total, the annual power consumption is reduced by 4.0 % without increasing the number of ON/OFF-operations of the components. This improvement is obtained solely by a better matching of pipes and pumps in the sea-water system leading to lower flow friction and hence reduced power consumption of the pumps.

An optimization of the plant design with an advanced management of the components results in a design that differs significantly from the optimal

design obtained with a simple management. First, the screw compressors should be of different sizes. Second, the sea-water pumps are found to be relatively small compared to the previous simple-management case. By the new design, the pumps are ordered sequentially in or out of operation as the load changes.
Simulating a week in August, the weekly power consumption is reduced to 111.9 MWh; in February the power consumption is 37.5 MWh. In all an annual reduction of 8.8 % is obtained, which is approximately half of the gains established as the target.

Figure 4. COP for an optimized design of the plant (with advanced management) with increasing load in the -6°C system. August.
($\longrightarrow$) : Q_{10} =   0 KJ/s.
($-----$) : Q_{10} = 1000 KJ/s.

For this design and operation of the plant, the COP-characteristic with increasing load in the -6°C system is shown in figure 4.

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Compared to figure 2, it is seen that the COP is raised significantly, particularly at low loads, and that the sudden changes with varying loads are smoothed noticeably. However, the required number of ON/OFF-operations of the screw compressors is very high and would not be acceptable.

Load management

For the design and operation of the existing plant, figure 2 shows that even small changes in loads can involve changes in component selection and therefore lead to significant changes in COP. By managing the load fluctuations, the plant can be made to operate on the best side of these sudden changes in COP, thus improving the COP.

In all there are more than 500 consumers and several of these are fermentation and storage tanks with a high thermal capacity. These, and several other consumers, are cooled discontinuously in short periods (ON/OFF), and their operation is presently not coordinated and is practically random. It is in this study assumed possible to perform a limited coordination of these consumers.

The weekly load profile has been simulated for the designs and management strategies listed in table 1 assuming different possibilities for a load management in the brewery. The extent of this management is expressed as the percentage of the loads (expressed by the weekly average loads), that could be advanced or delayed for a 2 hour period when following the present weekly load profiles in each utility system. At a load management of 20 %, a load of 400 KJ/s could be shifted in the -6°C system when following the weekly load profile in August.

The optimal strategy for the load management is found by two-dimensional dynamic programming [5]. The problem is two-dimensional because of the strong coupling between the two utility systems, both through the condensers and the screw compressors.

In figure 5, the weekly power consumption in August is shown for each of the optimized designs listed in table 1 with increasing degree of a load management in each utility system.

In the figure it is seen that both for simple and advanced management of the components, even a modest load management results in a significant reduction in the weekly power consumption. For larger values, the simple design and management of the plant approaches the power consumption obtained for the advanced design and operation.

It is seen that the targets are not reached. This is explained by the limited capacity of the seawater system (condensers and pumps) at high loads, which leads to a reduced COP. These high loads could be avoided and the target from section 4.1 reached, if the load management were increased.
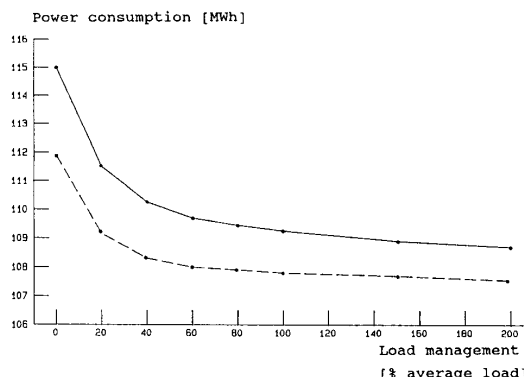

Figure 5. Weekly power consumption in August with increasing degree of load management.
(———) : simple design and operation.
(-----) : advanced design and operation.

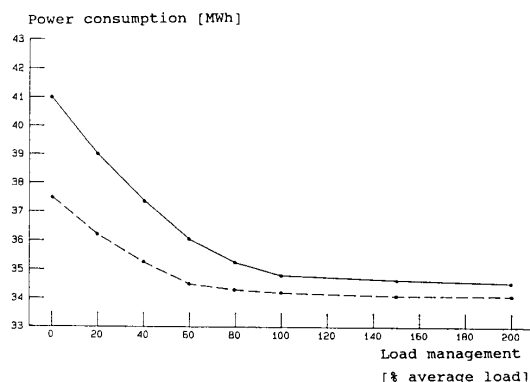In figure 6, the effect of the load management during winter operation is shown.

Figure 6. Weekly power consumption in February with increasing degree of load management.
(———) : simple design and operation.
(-----) : advanced design and operation.

For the winter operation it is seen, that a relative larger improvement is obtainable. Again, the gains by using load management are higher for a plant with a simple operational strategy than with advanced management. It is seen, that during winter operation, the target is obtainable for the values of load management investigated.

It is equally important, that the weekly number of ON/OFF-operations of the components is reduced when operating the plant with load management. However, with the advanced management of the components it would be necessary with extensive load management to reduce the weekly number of ON/OFF-operations to the present numbers. At the highest values of load management shown in figures 5 and 6, the weekly

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number of ON/OFF-operations of the screw compressors is approximately 40 % higher than the present.

A practical, combined approach

For a realistic, practical improved design and operation of the refrigeration plant, it is necessary to combine the different approaches illustrated above.

An improved management of the components would lead to a reduced power consumption, but would result in a significant increase in the number of ON/OFF-operations of the components.
Management of the cooling loads can lead to a significantly reduced power consumption without increasing the number of operations, but for real-life implementation, the degree of load management should be limited. Even though many of the consumers are in seemingly random operation, the cooling loads are strongly tied to the operation of the integrated brewery. For large values of load management, it is necessary to reconsider the operation of the total brewery. This is not realistic for an existing brewery. However, an advanced management strategy for the components would reduce the required degree of load management, as the plant can be operated in several more high-efficiency load points than with a simple management strategy.

By inspection of the many results, a practical strategy has been deduced. A significant reduction of the annual power consumption is obtainable when the plant design optimized for advanced management of the components is combined with 20 % load management and an management strategy allowing one small screw compressor to alternate between the two utility systems. With this design and operation, the weekly power consumption would be 110.0 MWh in August and 36.3 MWh in February, giving an annual reduction of 10.8 %.
With this design and operation, the COP will vary during the week as shown in figure 7.
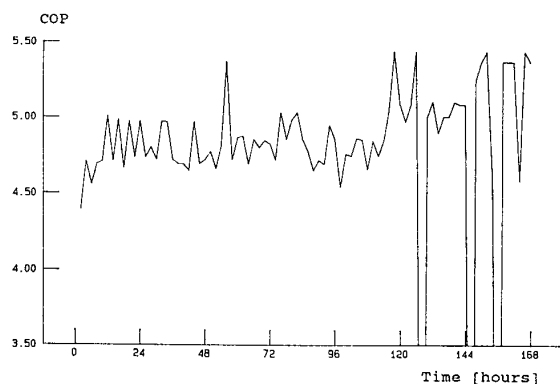
Figur 7. COP variation for the refrigeration plant during a week in August. Optimized design and operation, 20 % load management.

By this combination of component management and load management, the weekly number of ON/OFF-operations of the screw compressors is approximately 50 % higher than the present numbers, which is considered as acceptable. The number is far less than with the use of a fully advanced management strategy and illustrates the importance of load management.

CONCLUSION

A mathematical model has been applied to the study of the refrigeration plant in a brewery.
The usefullness of such a model is demonstrated through the results in which the improvements obtainable by design optimization, improvements in operational strategy and load management are weighed against the increased complexity of design and operation of the plant.
The study demonstrate the potential of a management of the numerous consumers in the plant. By a combination of design optimization, improved operational strategy for the components, and load management, electricity savings of 10 % is found to be practically obtainable as compared to an idealized target of 15 %.

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