Smart control of screw compressors in industrial conditions

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ABSTRACT

The compressors of a machinery room in food industries are often designed on the maximum refrigeration capacity required for the process, even if it is well known that this maximum requirement is effective a very scarce time fraction. Therefore, the compressors often run at partial charge. This situation lead to poor energy efficiency of compressors, and especially of screw compressors controlled with slide valves.
To partially solve the problem, the use of variable speed devices are recommended, guessing important energy savings.
This paper compares different control strategies of screw compressors in a machinery room of a dairy industry requiring 1 MW refrigeration and composed of 1 to 3 screw compressors of different size and models. It will demonstrate that a smart management of cascade and slide valve control delivers interesting results with a reduced investment cost. The interest of adding variable speed device on a selected compressor will be highlighted.
Keywords: industrial application, screw compressor, capacity reduction, slide valve, variable speed, control.

1. INTRODUCTION

The adjustment between cold production and needs is a key point when designing a refrigeration installation. Indeed, it is accepted that the design has to be based on the maximum reasonable need, knowing that the installation will work very few time at its maximum capacity.
Answering this question needs on one hand to have a good knowledge of the refrigeration needs (chronogram, histogram), and on the other hand, to dispose of actuators allowing to adjust the cold production. In industrial conditions, the use of screw compressors with slide valve is often proposed. In addition, variable speed devices are sometime proposed, expecting energy savings.
The drawing of the chronogram of refrigeration needs and the modeling of the performances of screw compressors controlled with slide valves and variable speed devices is therefore necessary to assess the performance of different control strategies.

2. DESCRIPTION OF THE INSTALLATION

2.1. Refrigeration needs

The studied installation is connected to a dairy process (sterilized milk, yoghurts and other flavored milk dessert). The process is based on the utilization of different equipments (pasteurizers, sterilizers, plate heat exchangers, blast coolers, …) fed with iced water. This iced water is produced with a MPG loop (-11°C / -6°C) in a plate heat exchanger with an adequate system preventing the exchanger's freezing. MPG is produced with an ammonia facility with a low pressure receiver feeding a plate heat exchanger (thermosiphon, cycle temperature : -15°C / +35°C). The MPG is also directly used in air coil heat exchangers located in storage facilities and in workshops. The refrigeration needs have been studied in detail with the production service and led to the following chronogram:

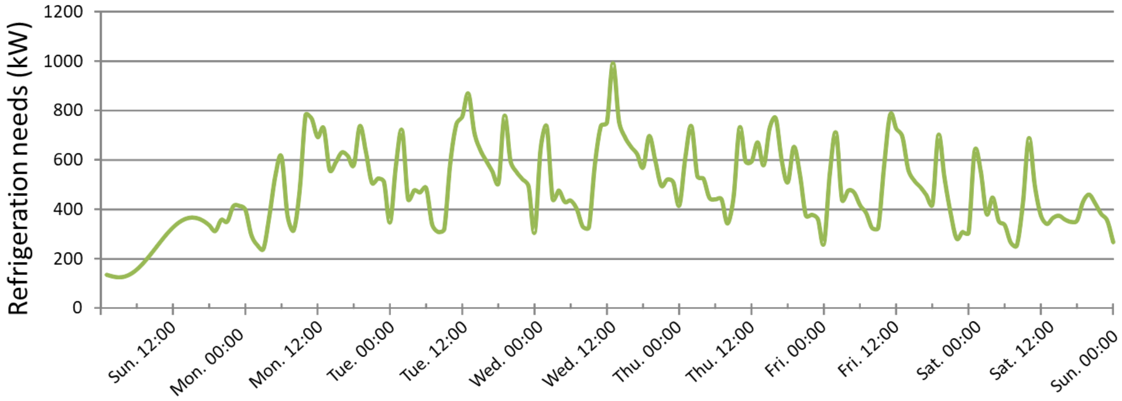


Figure 1 : Chronogram of refrigeration needs for a typical production week

This chronogram indicates following statistics:

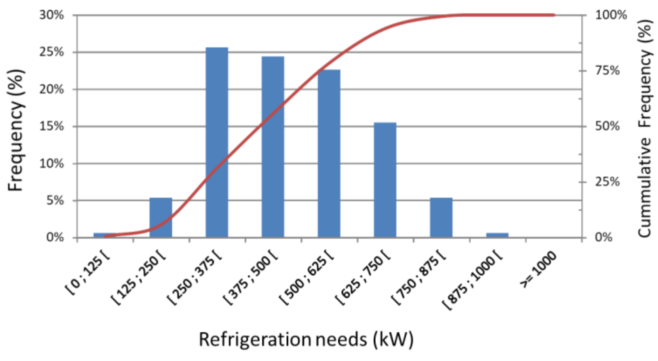


Figure 2 : histogram of refrigeration needs

Table 1. Statistics on refrigeration needs

Capacity (kW)	Frequency	Cumm.
[0 ; 125 [	1%	1%
[125 ; 250 [	5%	6%
[250 ; 375 [	26%	32%
[375 ; 500 [	24%	56%
[500 ; 625 [	23%	79%
[625 ; 750 [	15%	94%
[750 ; 875 [	5%	99%
[875 ; 1000 [	1%	100%
>= 1000	0%	100%
Max :	992	kW

The reading this data indicates that:

- the maximum need of 992 kW is only called for a short time on Wednesday afternoon
- most of the time, the refrigeration need is between 250 and 750 kW

Therefore, the choice of the number of installed compressor and of their control mode is of great importance.

2.2. Retained compressors models

For different reasons (including end-user requirements and habits), the use of GEA screw compressors is proposed. From this, different possibilities are studied:

- use of one big compressor (≈ 1 MW) fulfilling all the requirements and adjusting its refrigeration capacity with a slide valve
- use of two medium size compressors (2 x 500 kW)
- use of three compressors (250 kW + 350 kW + 500 kW)

Following table summarizes the main characteristics of these compressors (cycle temperature: -15°C / +35°C):

Table 2. Main characteristics of the selected GEA screw compressors

Model	Ref. capacity (kW)	Elec. Capacity (kW)	COP
LR-L2655S-28	282.4	90.4	3.12
MR-M2655S-28	371.2	116.4	3.19
RR-R2240S-28	562.8	162.2	3.47
WR-W2240S-28	1078.5	317.7	3.39

2.3. Studied control strategies

In order to adjust the production to the needs, different control strategies are studied and compared:

Strategy 1 : only one big compressor (1MW) in use, with capacity control with slide valve to adjust the production to the needs.

Strategy 2 : two medium compressors (2 x 500 kW)

Strategy 2.1 : 1st compressors with slide valve until 100%, then 1st compressor 100% + 2nd compressors with slide valve to adjust the production to the needs

Strategy 2.2 : 1st compressors with slide valve until 100%, then 1st + 2nd compressors at the same slide valve position

Strategy 3 : three compressors (250 + 350 + 500 kW))

Strategy 3.1 : small compressor with slide valve until 100%, then small compressor 100% + medium compressors with slide valve to adjust the production to the needs, then small and medium compressors at 100% and big compressor with slide valve to adjust the production to the needs

Strategy 3.2 : small compressors with slide valve until 100%, then small + medium compressors at the same slide valve position, then all compressors to the same slide valve positon.

These strategies are completed with the use of variable speed devices, this device being installed on the biggest compressor for the strategy 3.

The comparison of the performances of these different strategies requires the modeling of the performances of each compressor working with slide valves and variable speed devices.

3. MODELING THE PERFORMANCES OF COMPRESSORS

3.1. COP vs slide valves position

Due to international recirculation of sucked gases (Moseman, 1999), the slide valve position has a direct and important impact on the coefficient of performance as shown Fig. 3.

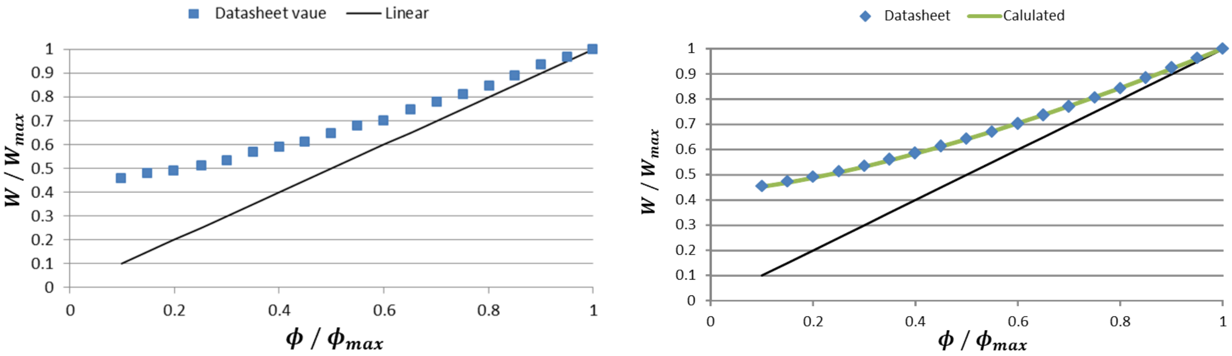


Figure 3 : Impact of the slide valve position on a screw compressor performance

These figures come from the data selection sheets of the compressor provider. It indicates that when the slide valve is in “low” position (corresponding to low refrigerating capacity), the performances or compressor decreases dramatically. As the relation between the slide valve positon and the reduction capacity is quite complex to establish (Widell 2010, Chen 2011), we will directly adopt the reduction capacity (ϕ / ϕ_{max}) as an input to our approach.

We propose to model this decrease by a power law inspired by pressure drop laws as followed :

$$\frac{W}{W_{max}} = \alpha \left(\frac{\phi}{\phi_{max}}\right)^n + \beta \qquad \text{Eq. (1)}$$

where :

W is the electric power input of the compressor (kW),

ϕ is the refrigeration capacity (kW)

α and β are calculated by forcing the function through two points :

- one point coming from datasheet, for instance the ratio $\frac{W}{W_{max}}$ indicated on compressor’s datasheet for $\left(\frac{\phi}{\phi_{max}}\right) = 0.1$
- the second point coming from the limit $\left(\frac{\phi}{\phi_{max}}\right) = 1$, where $\frac{W}{W_{max}} = 1$, leading to $\beta = 1 - \alpha$

The exponent *n* is adjusted to minimize the sum of the squared differences between the datasheet values and the calculated values.

Table 3 indicates the values of α and *n* obtained for the selected compressors. Fig. 4 shows the quality of the fitting, all coefficient of correlation being greater than 0.999.

Table 3. α and *n* coefficients used in Eq. (1) for selected compressors

Model	α	n
LR-L2655S-28	0.566	1.424
MR-M2655S-28	0.564	1.432
RR-R2240S-28	0.578	1.404
WR-W2240S-28	0.568	1.437

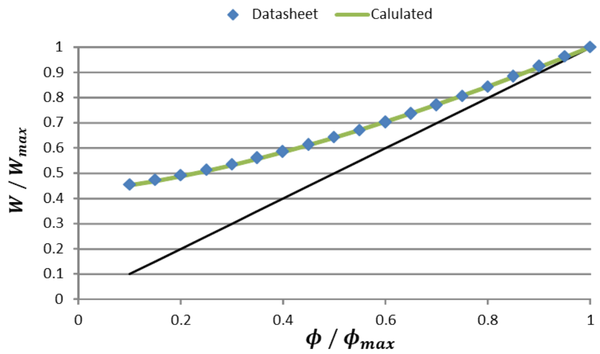


Figure 4 : example of fitting for compressor WR-W2240S-28

3.2. Introducing a variable speed device

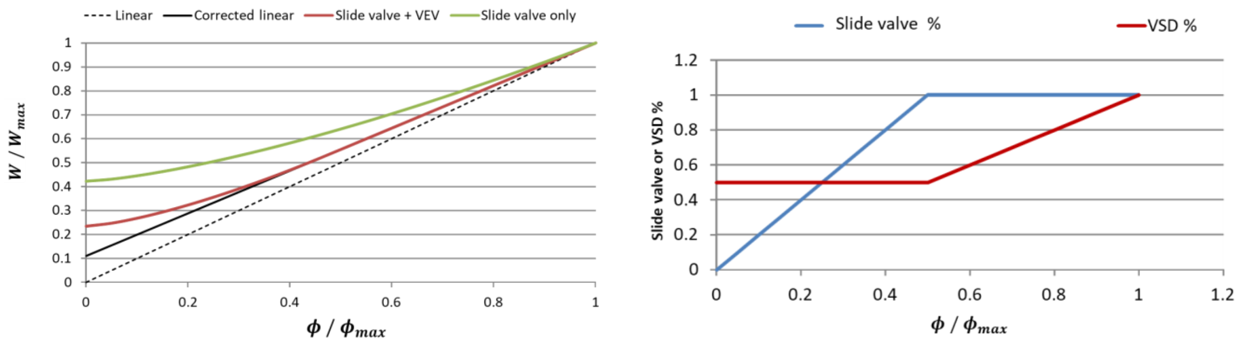
In order to better adjust the refrigeration capacity to the refrigeration needs, the implementation of variable speed device on compressor is often recommended. It is well known that these VSD allow energy savings. It is also well known that the efficiency of the electric motor somewhat decreases with the adopted frequency, and that a low limit of frequency has to be fixed in order to prevent lubrication concerns and motor warming-up.

VSD can be implemented in complement of slide valve action :

- While VSD low limit is not reached, VSD is actioned in proportion of the needs
- Below this limit, VSD is fixed to the minimum possible value, and the refrigeration production is adjusted to the need by acting the slide valve.

As a first approach, we propose to model the consequence of both actions on the performances of compressors by moving the base line (linear behavior between 0 and 1) to a affine straight line defined as: $y = A\ x + (1 - A)$ where $A = \left(\frac{1-\eta_{min}}{1-x_{min}}\right)$, $x = \frac{Freq.}{50}$, $Freq$= applied frequency (Hz) and η_{min} =motor efficiency at $Freq_{min}$.

Fig. 5 illustrate the assessed performance of compressor WR-W2240S-28 with la limit of VSD fixed at 25 Hz (that is ϕ / ϕ_{max} = 50%) and with η_{min} =90% at $Freq_{min}$= 10 Hz.



a- performances of the compressor

b- Position of actuators

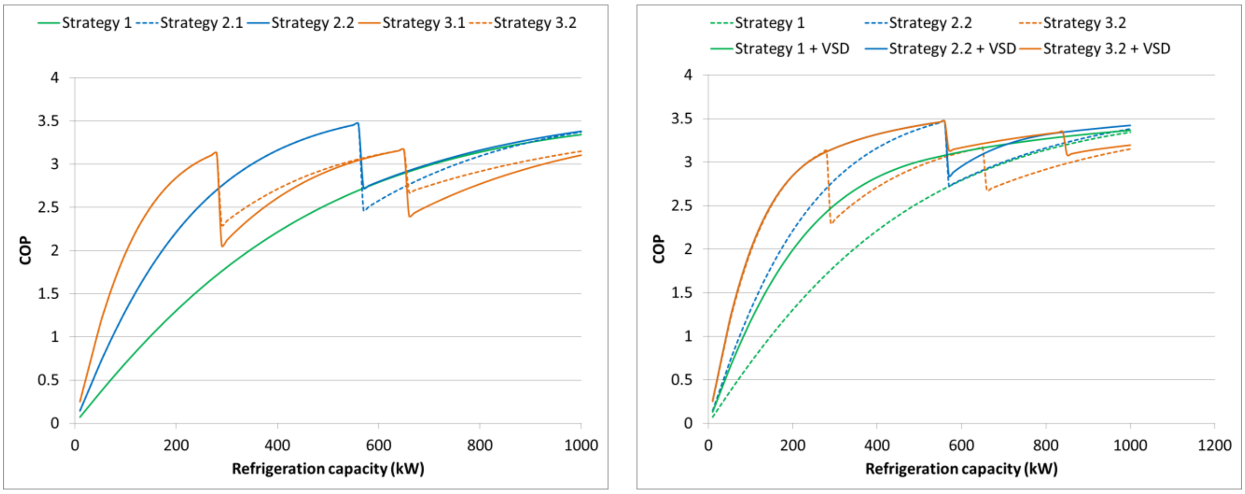
Figure 5 : Performance of a screw compressor associating slide valve and VSD

For some compressors, the low limit of acceptable frequency could be lower, especially if a lubricant pump and an additional cooling system of the motor are installed. The maximum $Freq$ could also be geater than 50 Hz. These two points would further improve the benefits of VSD.

4. EVALUATION OF DIFFERENT CONTROL STAGTEGIES

The approach presented above allows the assessment of the performances of compressors when their refrigeration capacity is adjusted by using slide valve and/or variable speed device.
The different control strategies introduced in paragraph 2.3 are compared in Fig. 6.

4.1. Evaluation of Coefficient of performances



a- without VSD b- With VSD on the biggest compressor

Figure 6 : COP of the different control strategies vs refrigeration capacity

The observation of Fig. 6 indicates that :

- The use of only one big compressor (strategy 1) delivers lowers COP, even if VSD is used in complement of slide valves
- The use of two compressors (strategy 2) delivers better COPs, especially at low charge when using VSD
- The use of 3 compressors delivers the best COPS on a wide range of refrigerating capacities, and especially at low charge.

It also appears that the global energy consumption of the installation depends on the histogram of refrigeration needs.

4.2. Evaluation of energy consumption

In order to assess the best strategy to be retained for the studied case, these results are applied to the chronogram presented paragraph 2.1.
Results are presented in the table 4

Table 4. Weekly electric consumption of the different studied strategies

	MWh / week
Strategy 1	33.0
Strategy 1 + VEV	27.5
Strategy 2.1	27.4
Strategy 2.2	26.7
Strategy 2.2 + VEV	25.2
Strategy 3.1	29.6
Strategy 3.2	28.5
Strategy 3.2 + VEV	24.8

5. CONCLUSION

For the chronogram corresponding to the studied application, it is confirmed that:

- the fractionation of the refrigerating capacity led to lower energy consumptions : for the studied case, installing 2 or 3 compressors instead of a big one allows to reduce the energy consumption of 15 to 20%.
- the use of variable speed devices (on the biggest compressor) led to substantial energy savings : for the studied case, it allows to reduce the energy consumption in between 5 and 15% depending on the number of installed compressors.

For the studied case, the installation of 3 compressors with VSD on the biggest of them led to the lowest energy consumption. For instance, and compared to the lowest investment cost (only one big compressor without VSD), savings of 8.2 MWh / week – it is 410 MWh / year can give precious information on the payback time necessary to balance the incremental investment cost.

It is important to mention that a different histogram of refrigeration needs would lead to somewhat different result. For instance, a histogram centered around high refrigeration needs would privilege the functioning at high charge, and therefore would disadvantage the use of small compressor – generally presenting poorest COP at high charge than bigger compressors.

Nevertheless, the approach presented in this paper would benefit to be used for many industrial configurations.

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