1980

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Airila, M., "Analytical Research into Throttling Control Methods of Liquid -Cooled Rotary Screw Air Compressors, to the Purport of Minimizing the Energy Systems" (1980). *International Compressor Engineering Conference.* Paper 352.
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ANALYTIC RESEARCH INTO THROTTLING CONTROL METHODS OF LIQUID-COOLED ROTARY SCREW AIR COMPRESSORS, TO THE PURPORT OF MINIMIZING THE ENERGY COSTS

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ABSTRACT

Capacity control by throttling of a liquid-cooled screw compressor, running at constant speed and producing compressed air, is an inferior method when the energy-economic point of view is taken into consideration. Manufacturers have tried to develop various kinds of control combinations tended to improve the energy economy. To a certain degree this has been successful, but incomplete knowledge about an optimum, theoretic control combination has been in the way of a really ideal control.

A linear, mathematical model for an ideal screw compressor has been developed. The model shows the dependence of the power consumption of the compressor on the pressure and on the air output. By the aid of the model the energy consumption of the compressor is analyzed in two basic ways of control: by the modulating control and by the on/off line control, to which the reduction of counter-pressure by idling is combined. As a final conclusion from the analysis the criteria are obtained, on the basis of which an energy-economically correct control method can be chosen when the consumption of compressed air is known. It is found that between the modulating control and the on/off line control there is a certain consumption limit, and when the consumption not reaching this limit, the on/off line control, on certain presumptions, is more advantageous than the modulating control. A further presumption for the on/off line control to be advantageous is that the pressure difference ranges between suitable limits. These limits can be determined by the aid of the model. The limits can most substantially be influenced by varying the volume of the compressed air network. In the on/off line control the optimum pressure difference depends both on the volume of the network and on the extent of consumption, and it can be definitely determined when the aforesaid parameters are known. The larger the volume of the compressed air network, the greater the savings reached by the on/off line control in comparison with the modulating control and the more freely the pressure difference can be chosen.

The model is adaptable with great accuracy also to a real screw compressor. The necessary amendments can be made on the numeric values of the parameters of the model, when the inferences concerning the model remain valid. On the basis of the inferences a computer program can be made out, which identifies the correct control type for all performance situations of the compressor.

INTRODUCTION

The investigation aimed to find out, by means of a simple model, how the throttling control of a screw compressor ought to be carried out energy-economically. The control systems available on the market have been designed "by the rule of thumb", without any exact criteria of, which is the control mode worth using in different loading situations. The investigation endeavours to give the basic philosophy for realizing the optimum control system.

MATHEMATICAL MODEL

The aim was to choose, to be used as a base for the analyses, a model, which would be linear in the relations to the most important variables, however, despite this, reasonably accurate. The final choice was a model of compressed air system where,in addition to the compressor, there are two compressed air receivers (Fig.1).

The receiver No.2 represents the joint volume of an eventual storing receiver and the compressed air network. The receiver No.1 represents the reclaimer of the compressor, where at the same time oil is separated from the air. The air pipe between the receivers is provided with a non-return valve which allows that the pressure in the receiver No.1 can be lower than that of the network. When the compressor runs idle, the pressure of the receiver No.1 is released to the level p_t.

The dependence of the compressor power need on the output rate x and on the compression ratio ε can be derived from the simple isentropic-isobaric cycle (Fig.2).
The power need can be formulated:

$$P = x \cdot p_0 \cdot \dot{V}_0 \cdot \frac{\overset{\gamma - 1}{(\varepsilon - \gamma)}}{\gamma - 1} + \frac{p_1 \dot{V}_0}{\varepsilon} \qquad (1)$$

which can be put into the following form:

$$P = a \cdot x + b \cdot p_1 \qquad (2)$$

In the coordinates P-x-p_1 the diagram of the equation is a plane (Fig.3), which goes through the origin.

In the Figs. 4 and 5 the results given by the model at the pressure ratio 8 and γ value 1.4 have been compared with the general measuring results. Van Ormer in the references [1] and [2] states that during the idle run at counter-pressure of the network power need of the compressor makes around 65-70 per cent of the maximum power. The dependency of the power need during idling on the pressure of the receiver No.1 has been estimated from the values given by different manufacturers. It can be seen that the model follows the real values partly even well.

The accuracy of the model can be improved by presenting it in a more general linear form:

$$P = a \cdot x + b \cdot p_1 + c \qquad (3)$$

ANALYSIS OF THE CONTROLLING PROCESS

The analysis is carried out on the basis of the diagrams on pressure - time and power need - time as per Figs. 6 and 7.

By applying the presented power need equation to the reasoning from the Fig.7,energy consumed during one sequence with the modulating control (= E_2) and with the on/off line control (= E_1) can be calculated. As their difference, the energy saving $\Delta E = E_2 - E_1$ is obtained. By examining the prefix of ΔE, those consumption degree and parameter regions are found where either control mode is superior to the other. By still finding out the maximum value for the expression $\Delta E/E_2$ as a function of time the optimum length for the sequence of the on/off line control can be searched out. By the help of the period length and the consumption rate the optimum pressure difference can be calculated.

By separate analyses and by letting x vary between 1 → y, it can be found out that x = 1 and x = y are the only control methods that are energy-economically feasible. In other words: the on/off line control and the modulating control are the only real alternatives.

The analyses were carried out also from the starting point that the initial pressure of the sequence is higher than the admissible minimum pressure p_m.

RESULTS

As a result of the analysis, unique values, although in the form of laborious equations, were obtained for the consumption rate y_{lim}, which separates the modulating control and the on/off line control from each other. Fig.8 shows the results that were calculated using certain values of parameters V_2/V_1 and p_t. With the y values existing above the curves only the modulating control is feasible. With other values the on/off line control is more profitable, provided that the pressure difference is chosen for the suitable region.

In Fig.9 there are values of the optimum pressure difference calculated at pressure p_t = 400 kPa when the parameter V_2/V_1 varies. In the figure also that pressure difference region is outlined where the on/off line control is more profitable than the modulating control. On this level the limit curve of the difference region therefore separates the modulating control and the on/off line control regions from each other.

Fig.10 is demonstrative of the importance of parameters V_2/V_1 in the on/off line control from the energy-economical point of view. The curves present with the p_t values of 400 kPa what percentage of the relative difference in energy consumption between the on/off line control and the modulating control is lost, if the parameter V_2/V_1 is decreased from the comparison point V_2/V_1 = 100. It can be seen that the losses grow strongly when the said parameter diminishes.

Fig.11 tells what the relative energy consumption differences are like, if, instead of the optimum pressure difference, in the on/off line control only a fixed difference in the whole region of $0 \leq y \leq 1$ is used. According to the example case (V_2/V_1 = 10 and p_t = 400 kPa) the differences are found quite small just in the region where the on/off line control on the whole is worth using.

Equivalent conclusions in a more complicated form were obtained also from the analyses where the initial pressure was higher than p_m.

As a final result a control logic scheme could be outlined.

Detailed analyses and annexes can be found in the literature reference [3], which will be published at the end of 1980.

CONCLUSIONS

The analysis made using the linear model tells that

1. Energy-economically it is worth while running the screw compressor only with the modulating control or with the on/off line control.

2. The on/off line control is more profitable, if the consumption rate is sufficiently low and if the pressure difference region is suitable. The limits to the consumption region and the difference region can be exactly determined, when the consumption rate and the parameters of the system are known.

3. In the on/off line control there is an optimum pressure difference depending on the consumption rate and parameters. By choosing the constant difference properly, the energy consumption difference compared with the optimum difference situation remains quite small.

4. The compressed air network volume has an essential influence on the energy consumption of the on/off line control, as well as on the saving reached with the on/off line control in a favourable case in comparison with the modulating control.

5. It is possible to make out a logic scheme, which in each operating situation states the most profitable control method. The choosing steps that are the base of the scheme can be adapted to a measuring and calculating unit that takes care of the choice and execution of the optimum control.

DEFINITIONS

ε = compression ratio = compression chamber volume ratio in the beginning and at the end of compression

p_1 = reclaimer pressure

p_m = minimum network pressure

p_t = reclaimer pressure during idling (on/off line control)

V_1 = reclaimer volume

V_2 = network volume

x = output rate = output as fraction of maximum capacity

y = consumption rate = consumption as fraction of maximum capacity

REFERENCES

1) VAN ORMER, HENRY, Capacity control influences power cost for your plant's rotary-screw compressors. Power, December 1976, p. 58-60.

2) VAN ORMER, H.P.JR., Liquid-cooled rotary screw air compressors, Part 3: Types of capacity control. Hydraulics & Pneumatics, May 1978, p. 85-88.

3) AIRILA, MAURI, An analytic research into throttling control methods of liquid-cooled rotary screw compressors to the purport of minimizing the energy cost. Ph.D.Thesis, Helsinki University of Technology, Department of Mechanical Engineering, Otaniemi, 1980.

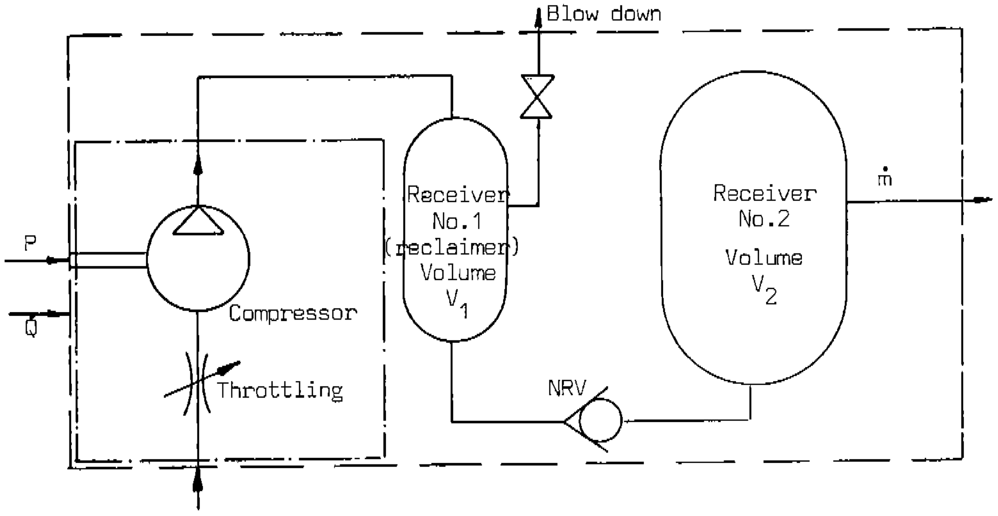


Fig.1: Model of screw compressor system

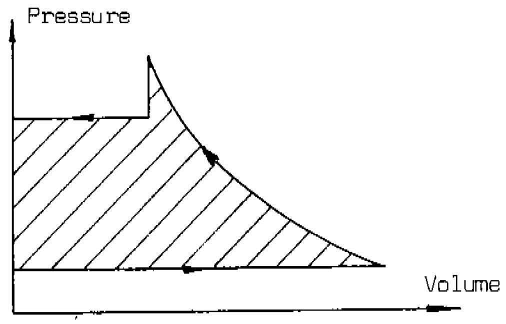


Fig.2: The isobaric-isentropic cycle of a screw compressor

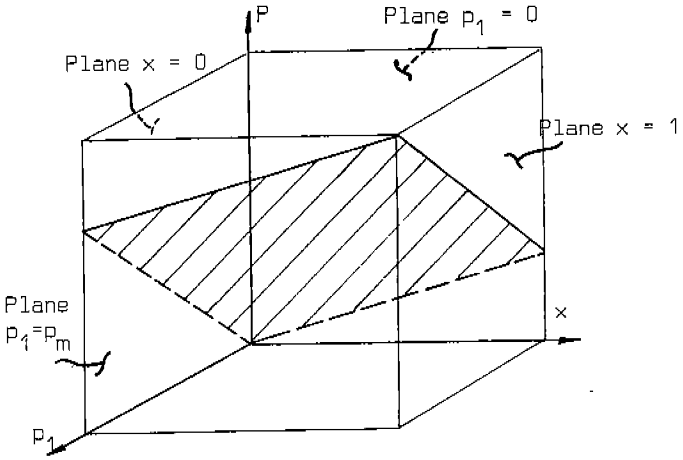


Fig.3: Working plane of screw compressor

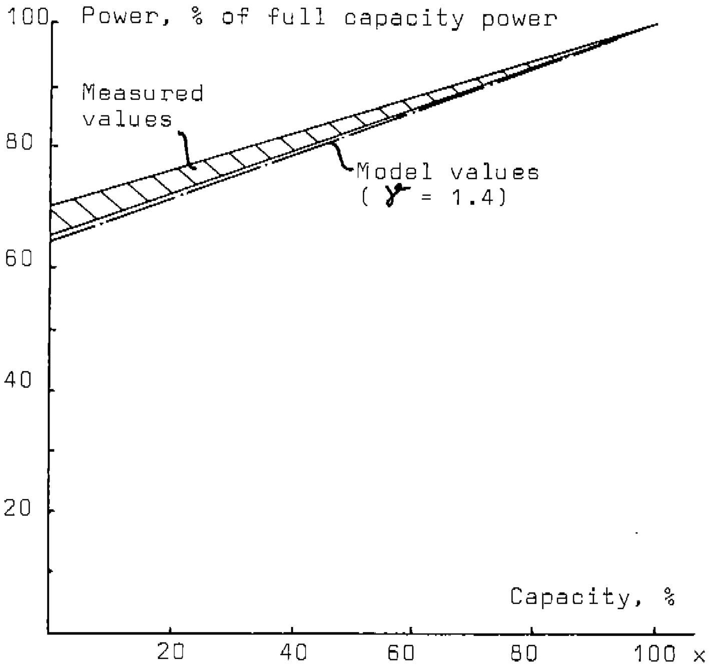


Fig.4: Dependence of power need on capacity when using the modulating control.

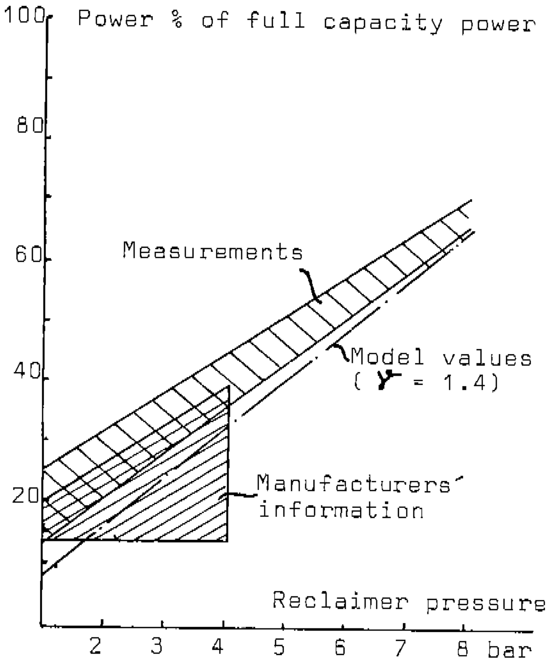
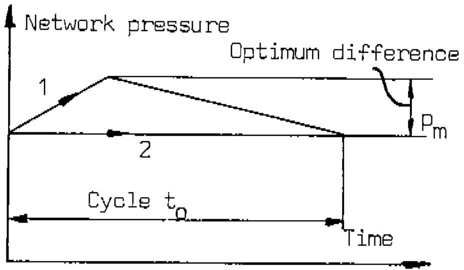


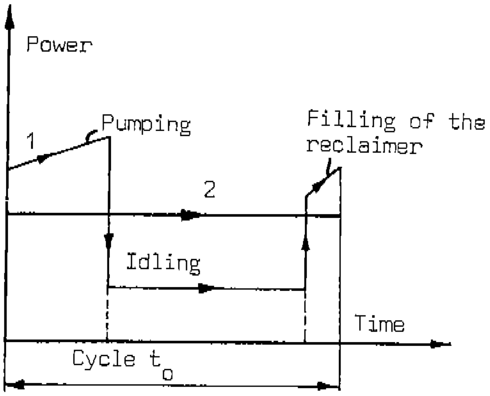
Fig.5: Dependence of power need on reclaimer pressure in idling.



1 on/off line control

2 modulating control

Fig.6: Network pressure in different ways of control.



1 on/off line control

2 modulating control

Fig.7: Power need in various control methods

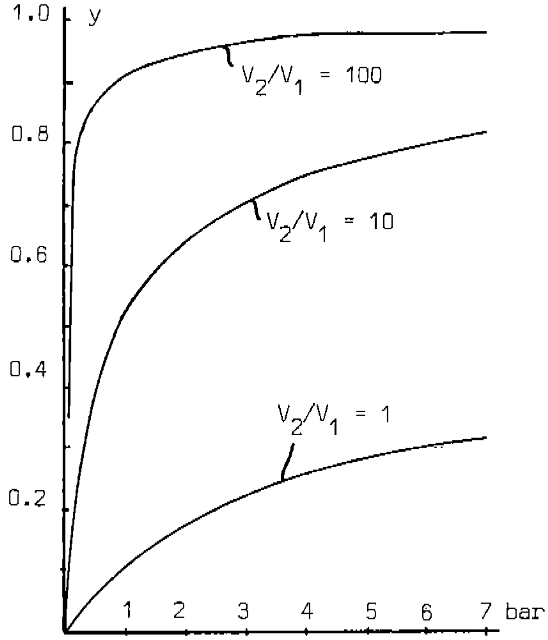


Fig.8: Difference between network pressure and reclaimer pressure

With the values of y above the curves, modulating control is positively more profitable than on/off line control.

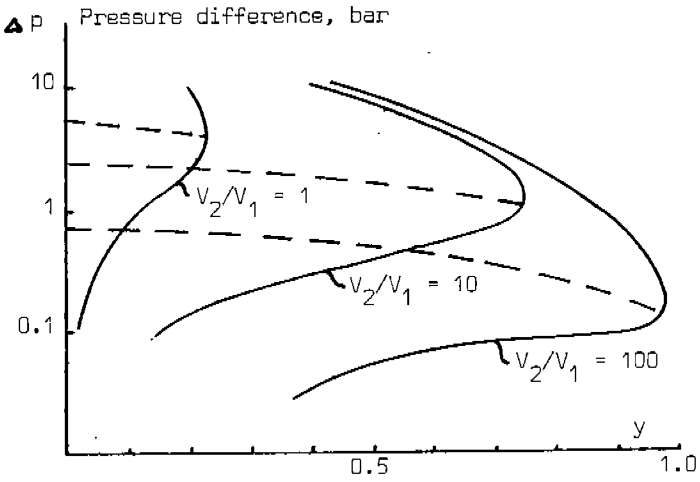


Fig.9: With Δp, y values existing to the left of the curves the on/off line control is more profitable than the modulating control.

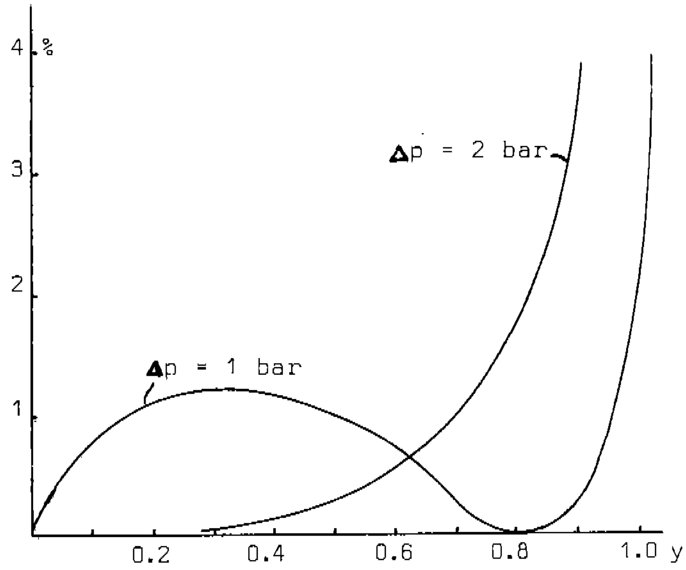


Fig.11: Additional energy consumption caused by the use of constant difference, compared with the use of optimum difference.

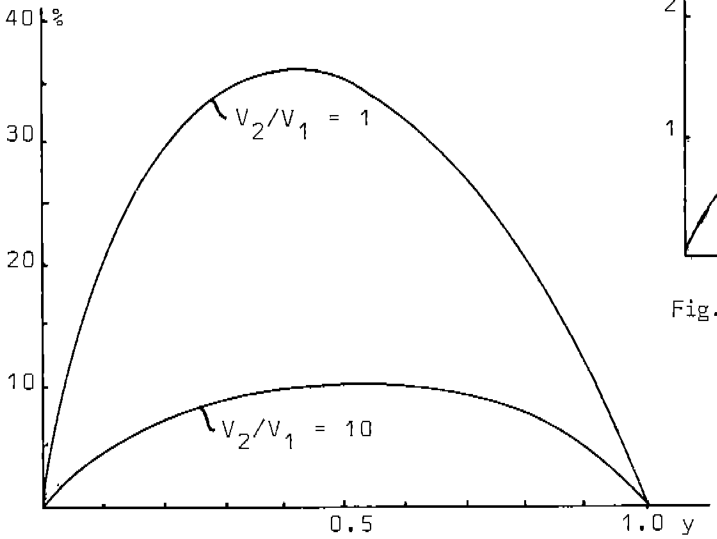


Fig.10: Loss of the savings to be reached by on/off line control when the ratio V_2/V_1 goes down from 100.