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REDUCTION IN POWER CONSUMPTION OF HOUSEHOLD REFRIGERATORS BY USING VARIABLE SPEED COMPRESSORS

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ABSTRACT

Although the energy consumption of individual household refrigerators is small, their large number represents an appreciable potential for energy savings. Improvements in insulation, compressor efficiency and optimisation of the refrigerant charge have reduced energy consumption significantly in recent years.

Still more power can be saved by converting the capacity control strategy from compressor on/off cycling to a variable speed running mode. This control strategy leads to a reduction in the average speed of the compressor and fewer stops, which are then only needed for the periodic defrosting of the evaporator. Numerical simulation showed that this kind of operation can lead to energy savings of up to 30%. The reasons for the savings are: Smaller friction losses in the compressor, higher evaporation temperature, lower condensing temperature and a reduction in losses associated with the pressure equalisation on compressor stops.

In the experimental investigation an off-the-shelf hermetically sealed compressor was modified for use with a frequency converter and installed in a household refrigerator. In a temperature-controlled chamber, energy consumption was measured according to DIN EN 153 at different compressor speeds. In nearly continuous running mode, the energy consumption was reduced by approximately 20% compared to the original on/off mode.

Furthermore we investigated experimentally and by simulation the difference between fully variable speed control and the operation with just two fixed speeds, i. e. switching between a low and a high speed according to the heat load. It turned out, that the difference in power consumption between these two control philosophies is marginal, in the maximum 3 %. Because the two-speed control can probably be realised at lower cost, it seems more advantageous to implement this control strategy in household refrigerators.

REQUIRED COOLING CAPACITY

Although the energy consumption of individual household refrigerators is small, their large number represents an appreciable potential for energy savings. Improvements in insulation, compressor efficiency and optimisation of the refrigerant charge have reduced energy consumption significantly in recent years.

The purpose of this investigation was to find out, how much power could be saved by optimising the capacity control. The control system has to make sure that the refrigeration provided by the refrigeration cycle matches the required cooling capacity. The required cooling capacity of a household refrigerator is the heat flow, which has to be removed through the evaporator of the refrigeration cycle to keep the average temperature inside the cooling cabinet at a level of e. g. 5°C. This required cooling capacity depends on

- the heat conducted through the insulation, which in itself depends on the ambient temperature
- the door opening frequency and duration
- the cooling-down of warm goods
- the water removal from moist goods

Since some of these parameters are varying with time, also the required cooling capacity will vary with time. The refrigeration, which has to match the required cooling capacity, is provided by the refrigeration cycle. Since the system has some thermal inertia, the matching has not to be instantaneous, but it must fit to a certain time-average of -say- about 20 minutes. The refrigeration cycle consumes electric power. The amount of consumed power does depend on the (time-averaged) required cooling capacity, the ambient temperature and the efficiency of the refrigeration cycle.

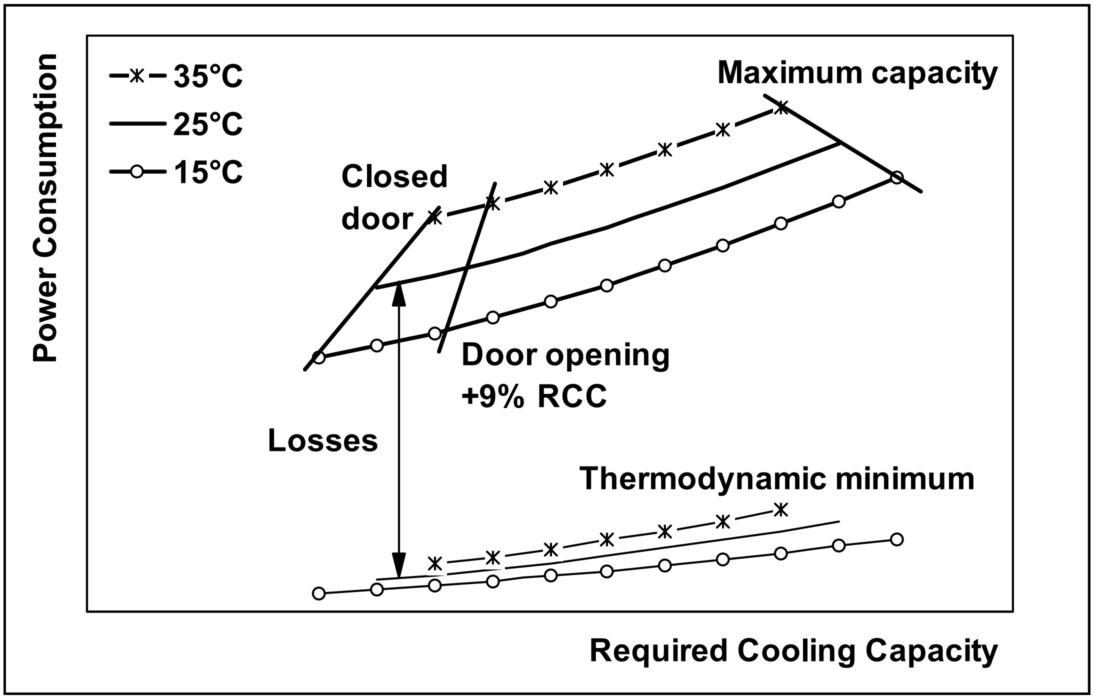

Fig.1 Performance map of the refrigerator

Fig.1 is a performance map of a household refrigerator. The abscissa is the required cooling capacity, which – as mentioned above – depends on a number of different influence factors. The ordinate is the power consumption. The map shows in three curves the power consumption for the ambient temperatures 15, 25 and 35°C in function of the required cooling capacity.

The limit on the left side of the curves is the “closed door” line with the minimum required cooling capacity. The upper limit of the curves is the “maximum capacity” of the refrigeration cycle. If the required cooling capacity exceeds this maximum capacity, the temperature in the cabinet will rise above the specified 5°C.

In such a performance map also the influence of a regular opening of the door can be shown. We have found experimentally [1], that one opening per hour with a duration of 20 seconds leads to an increase of the required cooling capacity of about 9 %.

Since the required cooling capacity and even the ambient temperature are varying with time, the required operating range of the refrigeration cycle of a household refrigerator is quite large. So an adequate capacity control is required. The traditional control method is the on/off control of the compressor. In this case the maximum capacity is determined by the refrigeration rate provided by the continuously running compressor.

But most of the time the system will work near the “closed door” mode. The power consumption in this very low capacity mode will have the largest influence on the power bill. So the task for the system designer is: Find a very efficient system for operation at low capacity, but also allow operation at a quite higher peak capacity.

LOSSES IN THE REFRIGERATION CYCLE

In Fig. 1 also the “thermodynamic minimum” energy consumption is shown. This is obtained by multiplying the required cooling capacity $\overset{*}{Q}_0$ with the Carnot factor, which is calculated with the absolute values of the desired cabinet temperature T_0 and the ambient temperature T_a.

$$P_{min} = \overset{*}{Q}_0 \frac{T_a - T_0}{T_0}$$

Apparently there is a large difference between the real energy consumption and the thermodynamic minimum energy consumption. This difference can be called “losses of the refrigeration cycle”. There exist several studies, how the total losses can be allocated to the different components of the cycle. Fig. 2 shows such an allocation published by Jakobsen in 1995 [2]. The majority of the losses come from the compressor with its motor, followed by the evaporator, the condenser and the capillary tube.

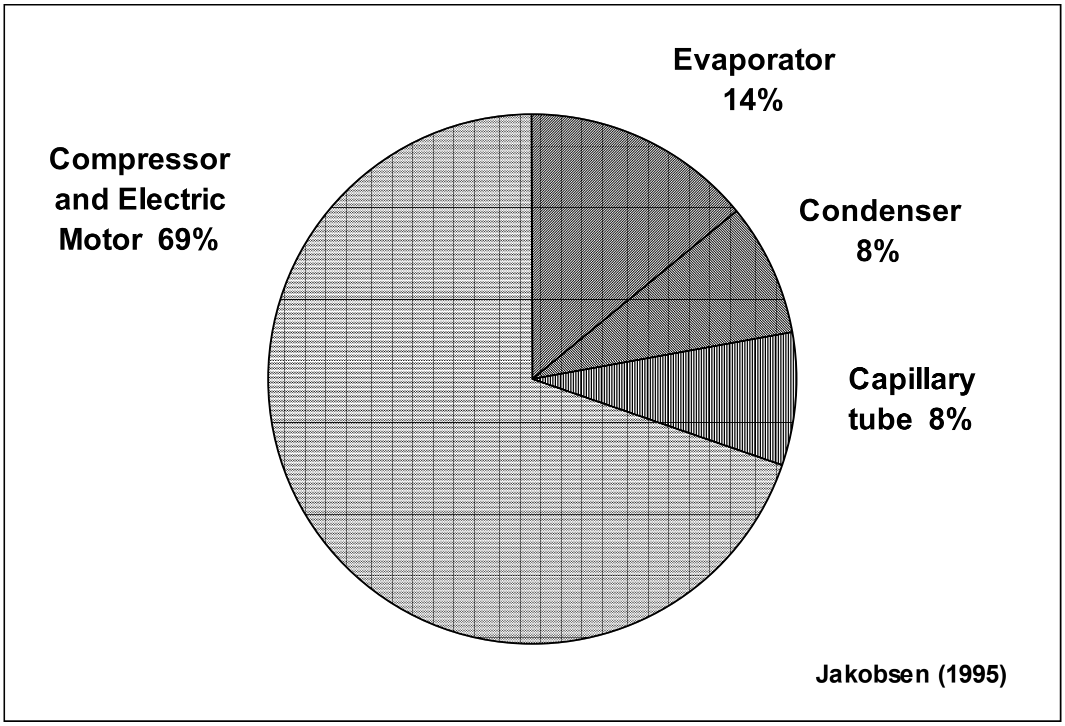

Fig. 2 Losses in the refrigeration cycle

A disadvantage of the presentation of the losses distribution like in Fig. 2 is that it does not show the portion of the losses, which are primarily caused by the chosen capacity control method. These “controls-losses” are not easily evaluated, because they can only be identified by comparing operation with two different control methods.

ON/OFF CONTROL

The usual control method is an on/off control of the compressor. The compressor is being chosen to cover in steady state operation a certain peak capacity. But most of the time the refrigeration cycle has to cover only the “closed door” requirements. So governed by the on/off control the compressor will operate only during a fraction of the time, but when it runs, then it runs on full capacity. Fig. 3 shows measurements of the high and low pressure levels of a refrigeration cycle operating with on/off control. The normal speed of the compressor is 3000 rpm. The compressor runs about 60 % of the time. The low pressure is rather low and the high pressure is rather high. When the compressor stops, the pressures equalize, which is connected with most of the refrigerant condensing into the evaporator, which is associated with an additional refrigeration load.

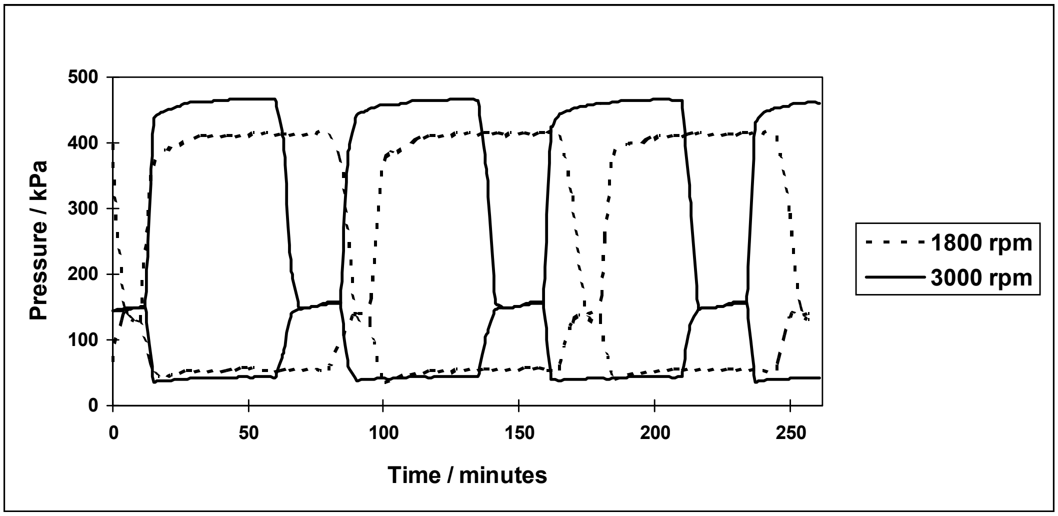

Fig. 3 Cycle pressures with different compressor speeds in on/off control

Fig. 3 also shows the operation of the same refrigeration cycle with a compressor speed of 1800 rpm. The relative "on-time" is somewhat longer, but the evaporation pressure is higher and the condensing pressure is lower and in total there are less on-and-off-switches.

Fig. 4 shows an "average" process in the p,h-diagram.

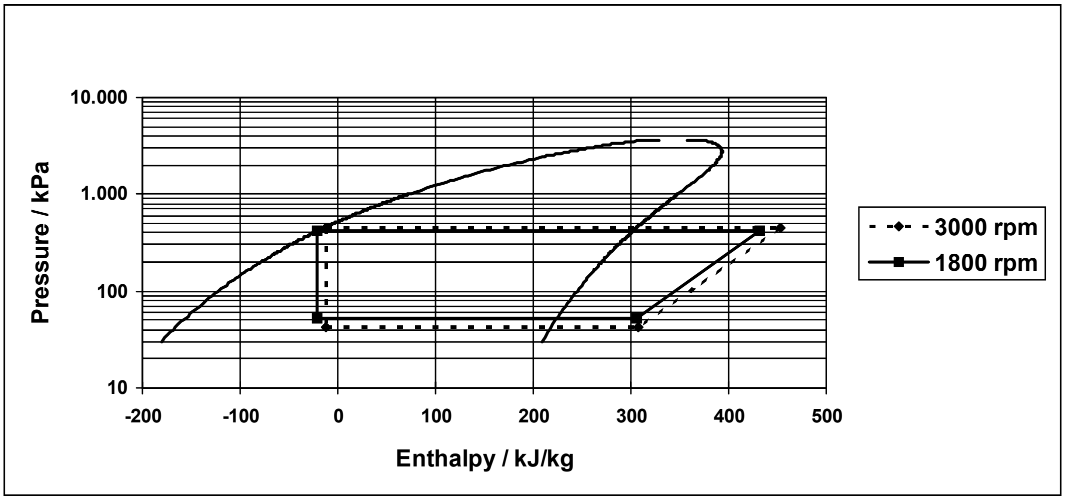

Fig. 4 Cycle with different compressor speeds in the p,h-Diagram

Fig. 5 shows the dependence of the energy consumption in function of the speed of the compressor, i. e. the plant is still being operated with on/off control, but when it is on, then at the selected speed. As an example, the resultant power consumption at 1800 rpm is about 21 % lower than at 3000 rpm.

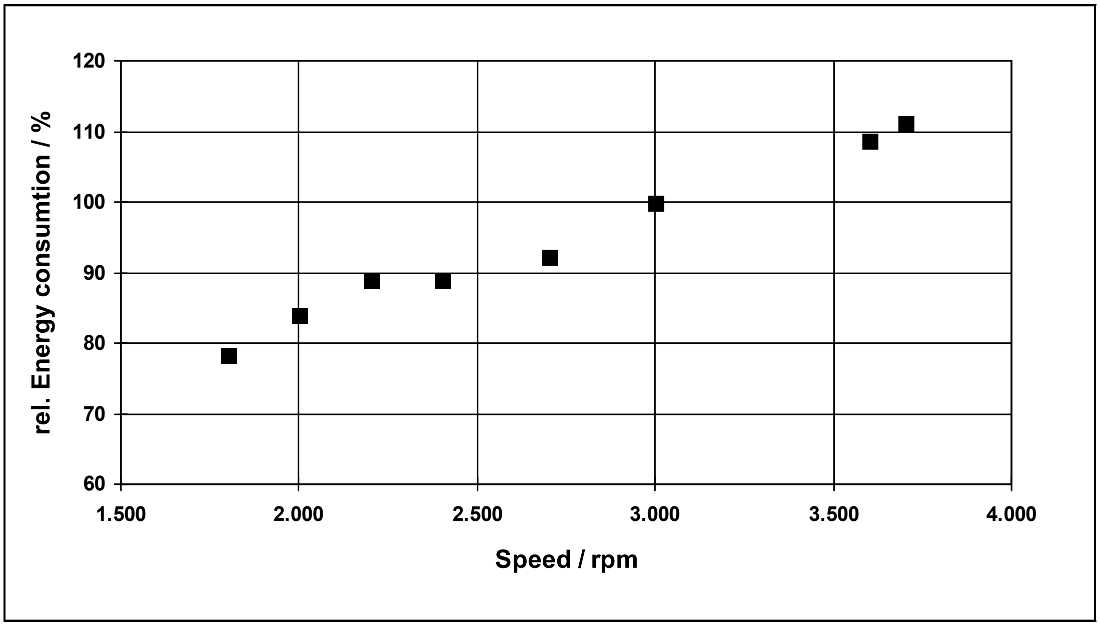

Fig. 5 Power consumption with on/off control and different compressor speed

CONTINUOUS OPERATION WITH VARIABLE SPEED

When inspecting Fig. 5, it seems obvious that an even further decrease of the speed would be beneficial up to a point, when the compressor does not have to stop any more and will run continuously at low speed. A saving of 30 % in power consumption in case of the “closed-door” operation looks possible. When the required cooling capacity increases, one could switch to higher speeds again. Therefore many compressor manufacturers have started to develop and sell hermetic compressors with variable speed drive. Thus one is able to always match the required cooling capacity.

One disadvantage of this solution is, that the electronics, which supply the variable frequency current, also consumes electric power, which may be in the order of magnitude of 2 to 5 % of the motor power. So one can ask, whether a continuous variation of speed is really necessary. An alternative would be to operate just at two fixed speeds: A lower one would cover about the “close door” operation, whereas the upper one would be designed for the peak load requirement. For demands in-between one would switch between the two fixed speeds.

CONTINUOUS OPERATION WITH TWO FIXED SPEEDS

In the following the power consumption of a system with a compressor with variable speed drive and a system with a compressor, which also runs continuously, but is switched between just two fixed speeds has been investigated by numerical simulation. For this we selected a low speed of 1800 rpm and a high speed of 3600 rpm. Figs. 7 and 8 show the resulting system temperatures. The simulation software used is a program by Philipp [3] adapted for this purpose.

For this simulation we chose a cabinet temperature of 1°C, because we wanted to use the existing set of parameters of our test refrigerator and compressor. At 5°C temperature in the cabinet, the 1800 rpm provided a still too large capacity for continuous operation.

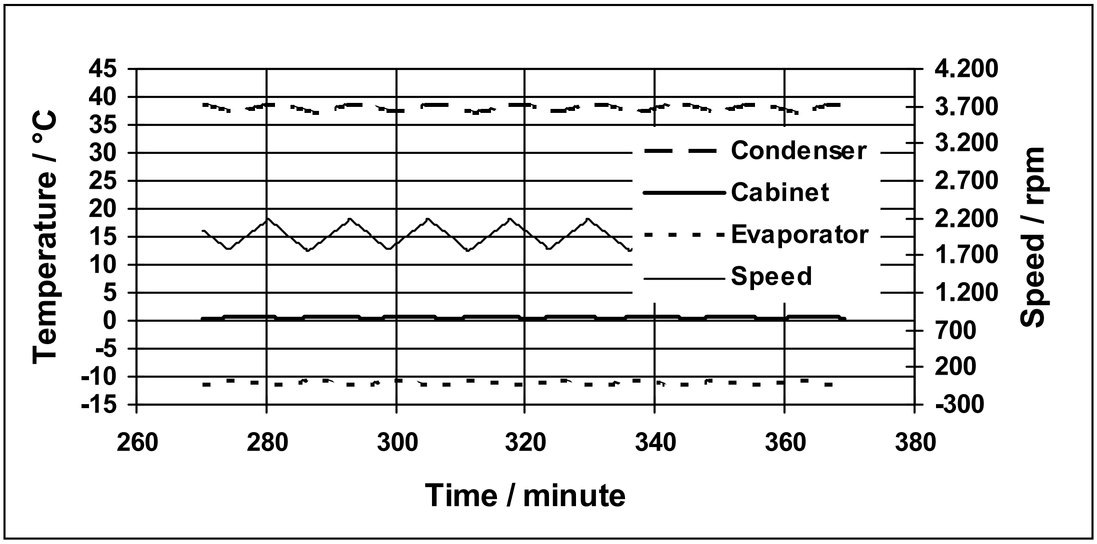

Fig. 7 Operation with continuously varying speed

Fig. 7 shows the operation with the continuously variable speed. Because some control is necessary, the speed varies linearly between 1760 and 2180 rpm. The evaporation and condensing temperatures hardly change.

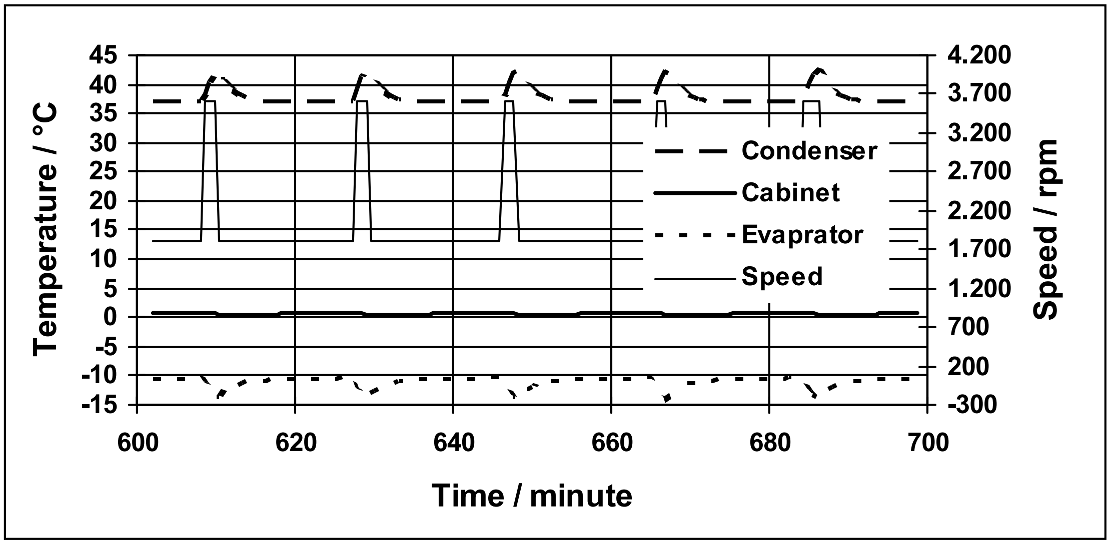

Fig. 8 Operation with two fixed speeds

Fig. 8 shows the temperature and speed for a compressor, which operates only at the fixed speeds of 1800 and 3600 rpm. Only for short periods the speed jumps to the higher value with consequential lower evaporation and higher condensing temperature. There are hardly any thermodynamic losses, which one can allocate to this jump in speed, because there is only a slight change in inventory between evaporator and condenser, not at all comparable with what happens during a compressor stop and start.

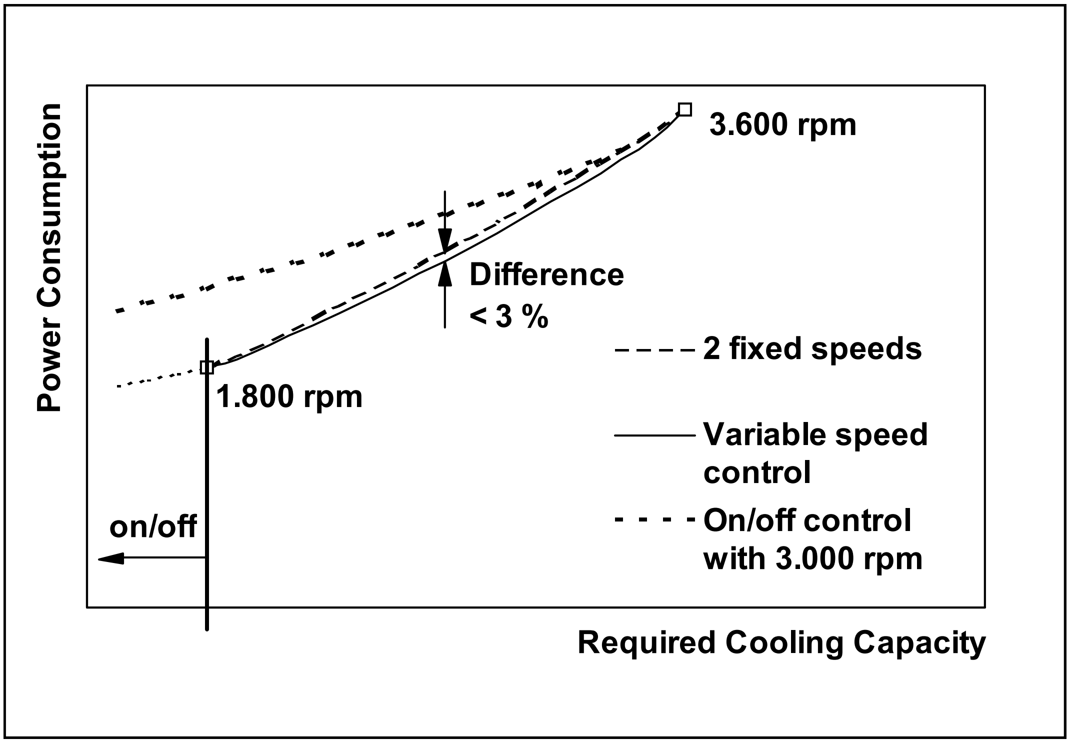

Fig. 9 Energy consumption in the whole capacity range

In Fig. 9 the power consumption for these two control methods have been compared for different required cooling capacities. The somewhat surprising result is that there is hardly any difference. This is true not only for the operation at very low capacities, i.e. the "closed door" operation, but also near the peak capacity, where both systems run continuously at high speed. The largest difference between the two modes is in the middle between the two extremes. But even there, the difference is less than 3 %. Also shown in Fig. 9 is the power consumption with the on/off control with a single speed of 3000 rpm.

For this comparison it has been assumed that the basic efficiency of the compressor and motor do not depend on the method of control. Also the power consumption of the frequency converter has not been taken into account.

In further experimental and numerical investigations [4] we found that the expansion in the capillary tube and the heat transfer in the suction line heat exchanger will be flexible enough to function well over a wide range of compressor speeds. Also the optimum charge of refrigerant does not vary with the compressor speed.

Only the conventional lubrication of motor and compressor was not sufficient at low speeds and had to be redesigned.

CONCLUSIONS

- Continuous running of the compressor at low speed can save up to 30 % power.
- Capillary tube, refrigerant charge and oil lubrication can be handled for variable speed operation.
- Concerning power consumption there is hardly any difference between continuous speed control and operation with just two fixed speeds.

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