Variable Capacity Compressors, a new dimension for refrigeration engineers to explore

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Abstract:

This paper presents the basic aspects in refrigeration system design using Variable Capacity Compressors. It is a practical guide for engineers that focuses on energy savings and noise reduction and illustrates an optimized design in only a few steps.

Main improvement areas for the sealed system as it relates to the compressor are discussed and trends for Variable Capacity Compressors performance are indicated.

Up to **a** 40% reduction in overall energy consumption and **a** 5 dB(A) average noise level reduction were measured applying Variable Capacity Compressors as compared to conventional fixed speed compressors.

Introduction:

Refrigeration systems are basically composed of one thermal insulated cabinet, designed to store and preserve food, that is equipped with a mechanism that takes thermal energy out from this ambient and keeps the low temperature inside compartments within defined limits. It compensates the heat leakage through the insulation and the added energy by atmosphere replacement during door openings or storage of hot goods.

This heat pumping mechanism for domestic refrigerators and freezers is called the Sealed System and consists essentially of a compressor, evaporator, condenser, a device that controls the gas flow, and the gas load. The correct design of each element depends of the type of system and specific required performance, and becomes more complex when sophisticated elements are applied like fan cooled heat exchangers, variable gas flow restrictions, variable capacity compressors, heaters, air flow control and others.

The complexity increases when multi-compartment systems are designed and the sophisticated devices are combined.
Going back to the basics for refrigeration systems design, there are some rules that help designers make choices for the basic elements when Variable Capacity Compressors are used, as well as to understand which elements are independent from this cooling capacity modulation. From these understandings it is possible to make some valid conclusions about trends for Variable Capacity Compressors performance, which orient future developments.

Optimization targets

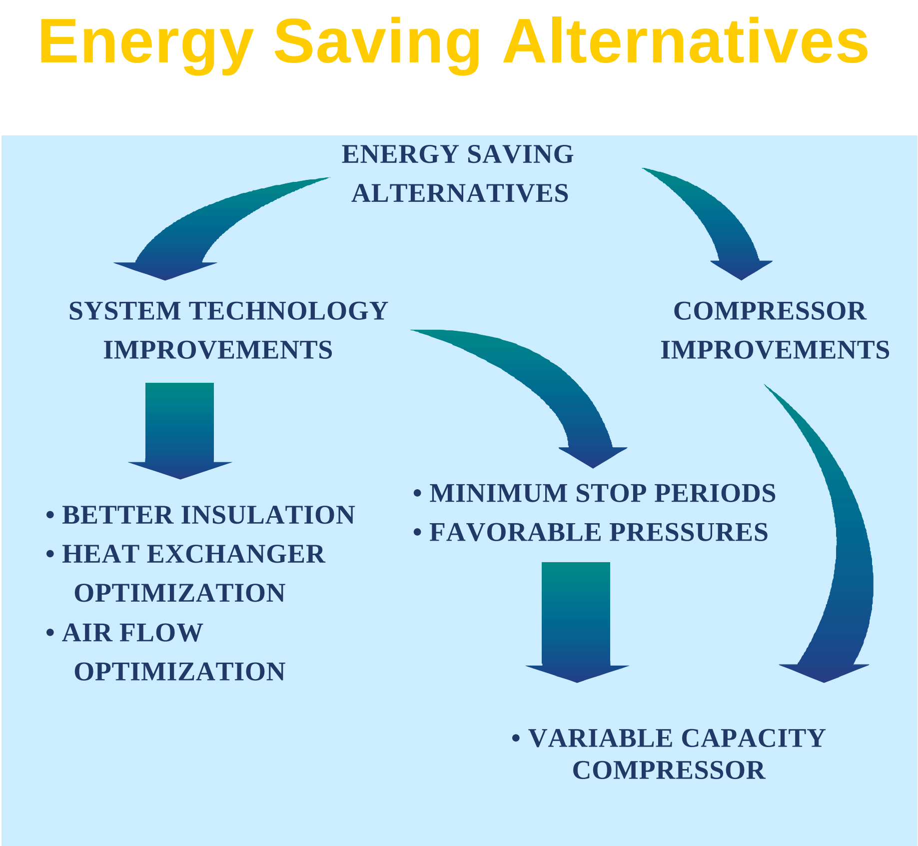
When a new appliance is designed, it becomes necessary to define the optimization functions. This means identifying performance targets to be accomplished with minimum additional cost.

Those performance targets could be a specific energy level, noise level, freezing capacity, cabinet temperature profile, internal volume or even some other specific target or combination of targets. Although not always easy to define, it is essential to define this Optimization target before a new design is initiated.

Energy Savings

The most important gain achieved by using Variable Capacity Compressors is reduction of energy consumption, which is achievable in a number of different ways, as shown in figure 1.

FIG 1 – Energy Saving Alternatives



It is clear that thermal insulation, the intrinsic compressor COP (Coefficient of Performance-which expresses the compressor's energy efficiency), and the thermodynamic behavior of the sealed system, are the basic areas with a fundamental effect on the appliance energy consumption, and can be worked independently to obtain benefits.

This technology imposes some limitations. For example, there is a compromise between Thermal insulation thickness and its performance, which affects appliance size, internal volume and cost.

Compressor Efficiency

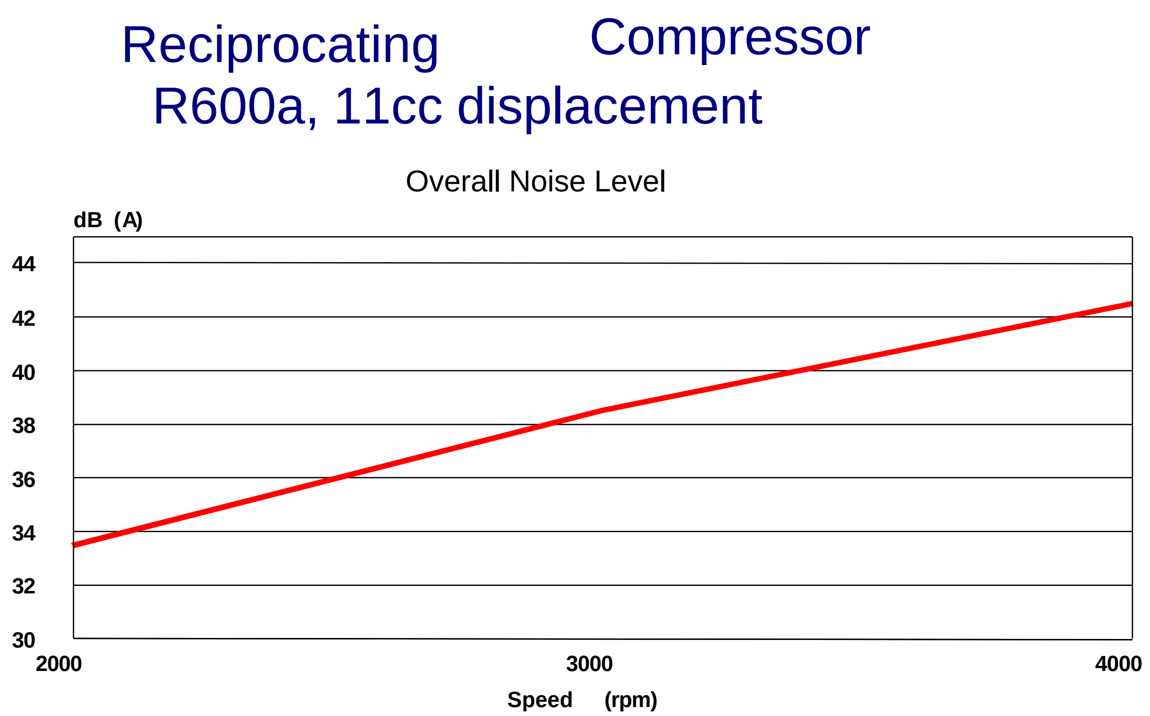
In case of compressor efficiency (COP), existing technology is also reaching limits for mechanical and electrical loss reduction, as described in the sequence.

Induction-type fractional horsepower motors used in fixed speed hermetic compressor today ave reached around 85 to 88% of efficiency. Mechanism losses are minimized by using low viscosity oils (ISO7) in combination with precise components and tied dimensional tolerances, as well as, specific techniques to improve gas flow and thermal behavior. The result is compressors with a COP around 6 Btu/Wh (1,76 W/W) at Ashrae condition.

Noise Reduction

The appliance's noise sources are the fans, mechanical switches, gas flow and the compressor. Compressor technologies have being improved in order to obtain lower acoustic noise emission, in all technical areas. These include shell design, internal transmission methods, cavity and component resonance, damping and noise sources. Even with technology evolution, the basic behavior always observed is the noise level dependence to compressor speed and cooling capacity, as showed in fig. 2.

FIG 2 – Noise

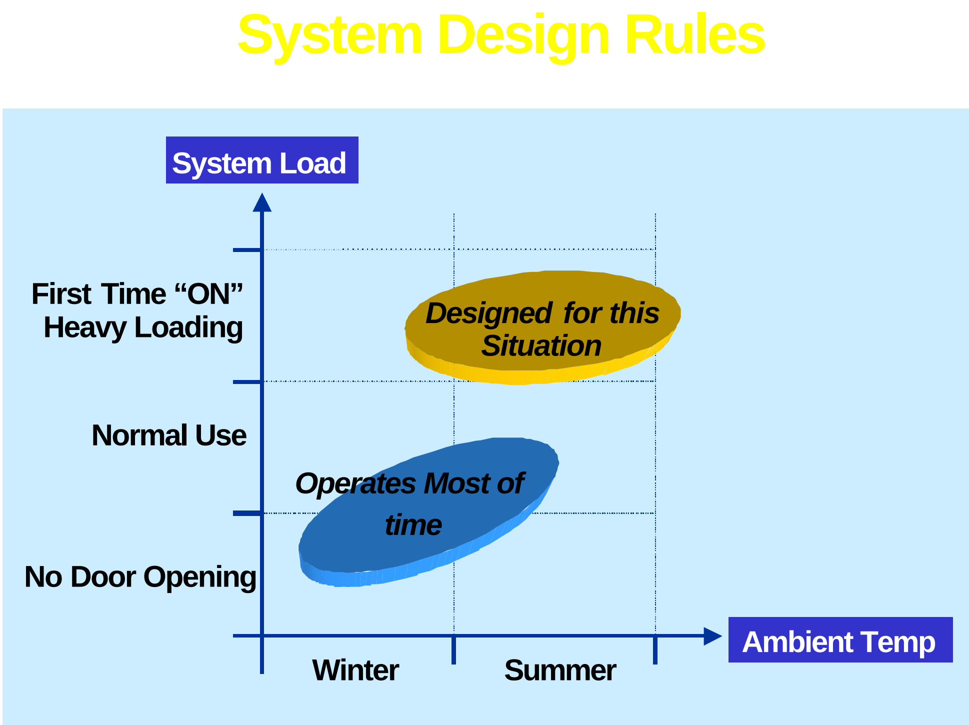


The Variable Capacity Compressor represents an excellent opportunity for a direct overall noise reduction in appliances, because it offers the possibility to operate most of time at speeds lower than 3000 or 3600 rpm.

Capacity Modulation Effect

In order to achieve the required pull down time, fixed speed compressors select the cooling capacity based on the maximum demand, at high ambient temperature, as illustrated in fig 3.
The consequence is that compressor delivers high cooling capacity, selected to overcome the worst condition, and it needs to be cycled on and off, when normal conditions is achieved. The results are "on times" typically from 30 to 60%, and consequent low COP during the running period, because of the high pressure drop between discharge and suction.

FIG 3 – Fixed Speed Design Rules



By using Variable Capacity Compressors, the cooling capacity can be adjusted according the appliance demand. Most of the time this capacity is much lower than the maximum cooling capacity the compressor can deliver, and the result is normal operation at low speed. The direct effect of compressor speed decrease is reduction of pressure drop between suction and discharge (lower mass flow), which causes the compressor to run more efficiently, compensating the longer periods it remains in "on state", and resulting in important energy savings.

From a thermodynamics perspective, the limitations for better performance focus on heat exchanger efficiency, that depends on its size and thermal coupling to environment, and depends also on pressure drop between discharge and suction. These are factors that affect the heat exchanger and compressor efficiency.
The use of Variable Capacity Compressors plays an important role in this aspect. This relates to the fact that there is the possibility to easily adjust the cooling capacity (mass flow) to the actual demand, create longer cycles, virtually close to the ideal "continuous operation", and minimize compressor start up losses and heat reflow losses. This promotes minimum pressure drops between discharge and suction sides, increasing substantially the "real COP" at the application.

Possible Appliance Features using Capacity Modulation

From a technical perspective, the Variable Capacity technology makes it easier to offer additional features which are preffered by the end user above and beyond energy savings and noise reduction. These include quick freezing and deep freezing. Inorder to achieve these features, compressors with conventional fixed speed technology, must be oversized. This oversizing increases the cost and noise levels, and reduces energy savings.

The system design for Variable Capacity Compressor

Following picture summarizes the interdependence of the components (FIG 4) and the basic routine for refrigeration systems design (FIG 5).

FIG 4 – Interdependence of the components

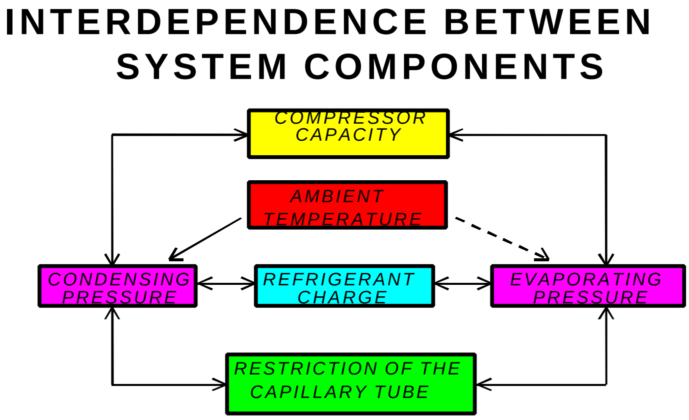
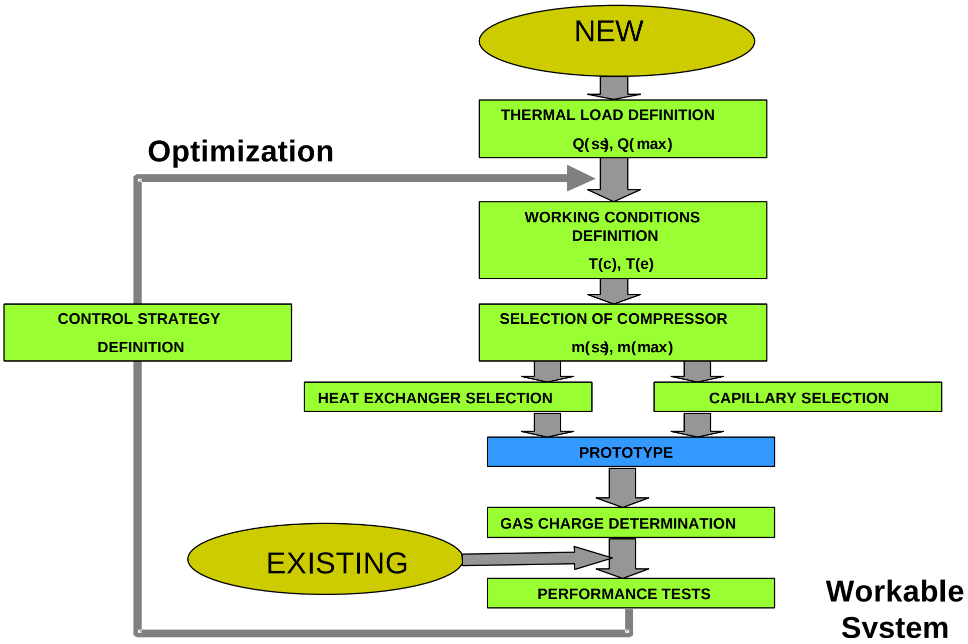


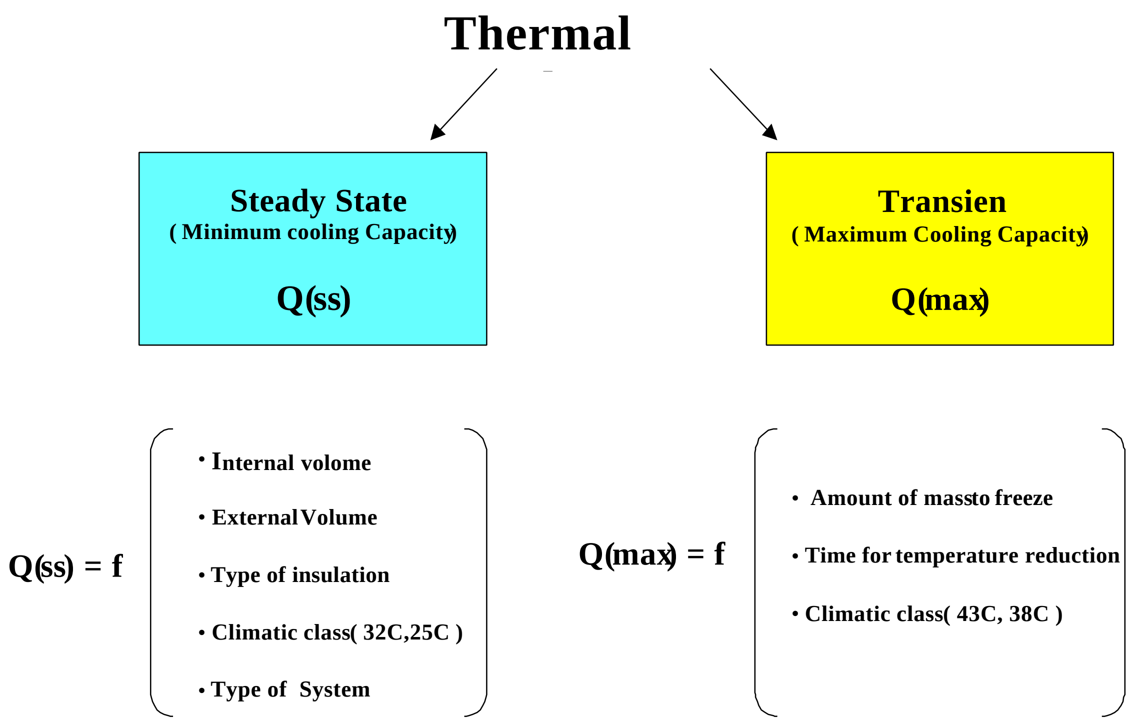
FIG 5 – Design Routine for Variable Capacity Compressor



Thermal load Determination

The Thermal Load must be determined when a new system is to be designed, as well as when any existing system is converted and optimized for VCC application. This thermal load definition depends on several factors as illustrated in Fig 6.

FIG 6 – Thermal load



Working conditions

Condensing and Evaporating temperatures, T(c) and T (e) can be defined based on experience.

Condensing temperature, T(c), corresponding to compressor discharge pressure, should be as low as possible, minimizing compressor stress, and reducing energy consumption.

Evaporating temperature, T (e), corresponding to compressor suction pressure, should be as close as possible to internal cabinet temperature, in order to maximize the overall efficiency.

Compressor sizing

The compressor is selected based on the minimum and maximum required cooling capacity. For Variable Capacity Compressors, the “Cooling Capacity” is no longer the correct way to identify a specific model. The compressor displacement (cubic centimeters) now becomes the convenient way to identify a model. Naturally, this is in correlation with the refrigerant used (R600a or R134a) and available speed range.

Maximum required cooling capacity comes from thermal load required in the worst situation. This **Q (max)** is the capacity needed to accomplish appliance performance at critical situations like pull down at high ambient temperature, or quick freezing, or deep freezing, whatever demands more cooling capacity.

Looking to compressor cooling capacity curves, at maximum speed, the lowest available compressor displacement, **D (a)** for this application is identified. It does not mean the compressor is already selected, it only mean the smallest model for this application was identified.

Now the minimum required cooling capacity must be defined. This comes from thermal load at steady state condition, **Q (ss).** As a first design step, the compressor is selected in order to accomplish steady state conditions, for energy consumption test.
Looking to compressor cooling capacity curves, now at minimum speed, the compressor displacement for steady state condition, **D (ss)** is identified. It is probable that D (a) is different from D (ss).

It is important to comment that keeping compressor running 100% of the time and adjusting speed to compensate the required thermal load at any time, in practice, is not the optimal point for energy consumption, because compressors do not keep COP constant when cooling capacity is reduced.

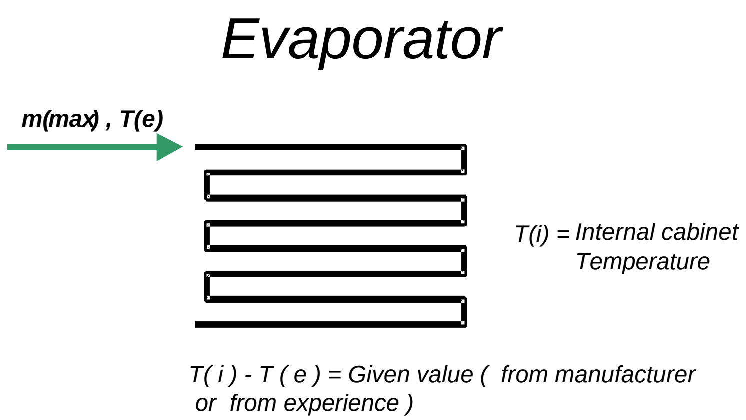
Compressors COP reduces as the speed reduces, which is due to fixed electrical losses. Smaller displacements also see a reduction due to fixed losses at the mechanism.

From several optimized applications using Variable Capacity Compressors, it was observed that the compressor may be oversized by a factor of 25 to 50% at “energy test condition”. This factor can be used to correct the determinate compressor displacement for steady state condition; D (ss), the first time the compressor is selected for a system, and in order to approximate the optimized point.
It is clear that during the optimization loop, the compressor, as well as the other components of the sealed system may be adjusted.

Evaporator

Based on maximum thermal load Q (max) and a given temperature difference between external ambient and gas, the evaporator is selected or designed, according to the specific rules or equations for the chosen type of heat exchanger. Fig 7.
Static or forced ventilation can be used, according to space restrictions or noise level requirements.

FIG 7 - Evaporator

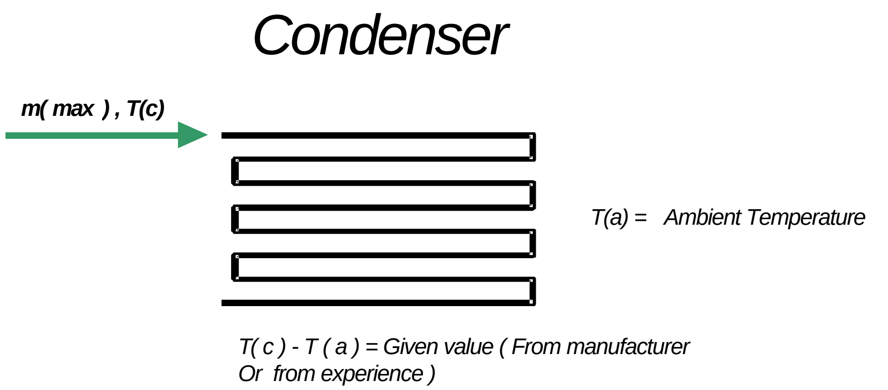


Condenser

The condenser is selected or designed based on maximum thermal load Q (max) and ~~a~~ given temperature differences between internal ambient of the cabinet and the gas, according to the specific rules or equations for the chosen type of heat exchanger. Fig 8.

It is well documented in technical literature that in order to optimize energy reduction, better results are obtained with forced ventilation, and in the case of freezers, specific care must be taken for the defrost cycle~~.~~

FIG 8 - Condenser



Capillary tube

The capillary is selected for steady state thermal load requirement Q (ss), in order to obtain the best energy performance.
It becomes necessary to know the mass flow for this condition, and what is obtained from compressor curves at working conditions T(c) and T (e), for minimum speed. For any thermal load higher than this level, when ambient temperature grows for example, the compressor speed will be increased, to increase mass flow, keeping evaporating temperature almost constant.

When deep freezing is requested, for example, the mass flow increases up to a level that evaporating temperature drops under the normal working condition T (e).

Prototype

After the previous steps, a prototype can be assembled.

Gas charge

The gas charge is determined based on the maximum ambient temperature the appliance may be exposed to in the field, and the maximum compressor cooling capacity at working conditions T(c) and T (e). Gas charge is considered optimum when the minimum temperature difference between evaporator inlet and outlet is achieved. At that point, the **"Workable System"** is available.

Optimization loop

Whenever a new appliance is designed or an existing appliance is optimized, a complete set of test must be applied to the “Workable System”. This gives references for necessary adjustments that may be needed to optimize the product.

During this part of the process, complete sets of tests are performed, and components are adjusted in order to correct any performance distortion that may appears. Based on test results and specific features the system offers, the optimized design is achieved at this stage, and the compressor working speeds can be defined.

For Variable Capacity Compressors, it is necessary to use a laboratory set up to make manual adjustments which allow the compressor to run at different speeds. During the first loop of the optimization process, separate tests must be carried out for each performance characteristic like energy, noise, defrost, freezing capacity, quick freezing, etc. The effects are combined in subsequent loops, already applying specific techniques like defrost optimization, noise control due gradual speed acceleration, and so on.

More sophisticated appliances, with many features and multicompartments offering individual temperature control, require a more sophisticated optimization process and a more sophisticated process to control all devices installed on this appliance. The result of this optimization will be a process (sequence of actions and decisions), that will be implemented as a software routine into the thermostat microcontroller. This process can be called as the “Control Strategy”.

Speed Control Strategy

Compressor speed is basically a function of thermal load, using the cabinet temperature as feedback information. As the cabinet temperature tends to overcome a defined “window” of desired temperature for this compartment, compressor speed is increased or decreased.

As mentioned before, the compressor is not kept running 100% of the time, and the compressor speed does not need to be adjusted continuously, unless a precise and stable temperature would be needed. In practice, some predefined speed steps are selected. According to the cooling demand, the compressor speed is then switched from one step to another step, with on-off periods when the stable condition is achieved.

Starting from minimum speed, the predefined steps of speed can be selected based on the energy performance tests, making the “Workable System” cycle ON and OFF at different speeds, in order to find the optimum point for energy. This is repeated for different ambient temperatures, resulting in “Preferred” speeds.
It is important to mention that those speed steps must be checked for noise or resonance from the system or components, and adjusted in order to avoid any problematic point.

The selected steps of speed are than introduced into the thermostat software, which will generate the speed command for the compressor.

Following is a graphical example, Fig 9, for different speed strategies, comparing Standard Compressors and Variable Capacity Compressors with a different number of speed steps.

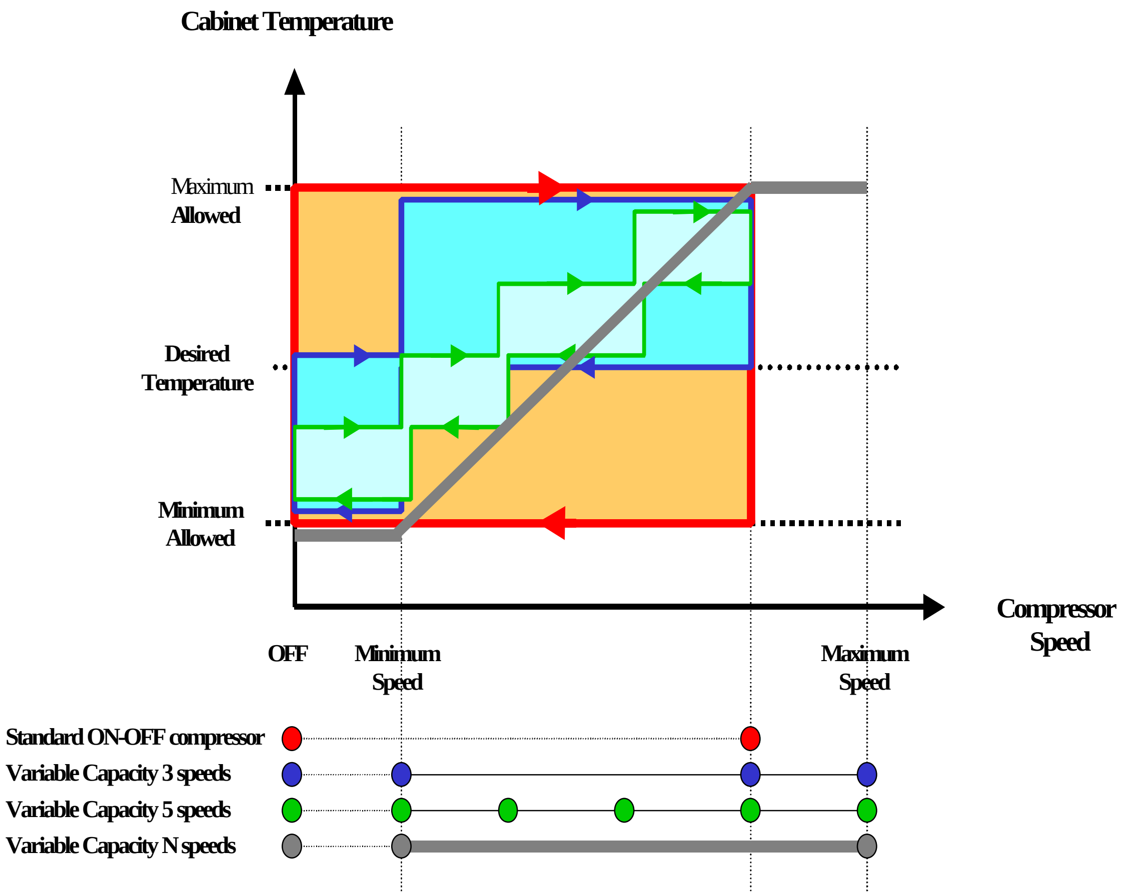
Tendencies for Variable Capacity Compressors

It is clear that the main advantage to using Variable Capacity Compressors is the drastically reduced energy consumption, which may be up to 40%. The two main areas for Variable Capacity Compressors improvement are found in the improvement of intrinsic compressor COP at low speed, where electrical losses and valves behavior are important, and the reduction of minimum speed, where it is a challenge to keep lubrication and bearing reliability. Another point for improvement is noise at high speed, where the same solutions for standard compressors are applicable.

The growing use of electronics in home appliances and specific growth of low cost variable speed drives will facilitate the mass use of Variable Speed Compressor in the near future.

The learning curve required for this specific technology is also a limiting factor. It demands revision of the fundamental aspects of appliance design.

FIG 9 – Speed Control Strategy



Conclusion

A basic routine to design and optimize appliances using Variable Capacity Compressors was presented, discussing the concept and defining some practical rules to approximate the optimal point during the first step of design. Taking into account the natural complexity involved in designing these kinds of appliances, a learning process becomes necessary, even when minor changes are required to optimize Variable Capacity Compressors application on existing systems.

Experience shows that improvements up to 40% are possible by applying Variable Capacity Compressor to existing systems, and much more value can be added to new designs using this new technology.

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