

Energy-Efficient Air Conditioning Systems Utilizing Pneumatic Variable Compressors

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ABSTRACT

Air Conditioning systems with reheat reduction based for energy efficiency have generally been implemented with either electronic variable compressors through active stroke control or with fixed displacement compressors through modifying the cycling set point. The present work demonstrates a unique concept of achieving energy efficiency via cycling a pneumatic variable compressor at elevated set points. The energy efficiency of such a system approaches that of an electronic variable but significantly higher than that of a fixed displacement compressor system. The cost of the system, on the other hand, is substantially lower than that of an electronic compressor. Secondary benefits include a softer start than with a fixed compressor and a considerably simpler control scheme than that required by an electronic variable compressor.

INTRODUCTION

As a capacity control method, cycling of fixed displacement compressors has been used since the beginning of mobile air conditioning systems. Under moderate or low thermal load conditions, excess capacity of the air conditioning system designed for soak and cool-down now poses a problem of excess: the air cooled by the evaporator of the air conditioning system is so low in temperature that the condensate from the air stream becomes iced and blocks further airflow to be discharged to the passenger compartment. The preferred method for controlling the excess capacity is to turn the compressor momentarily off by using a switch

which is installed in the refrigerant line and sensitive to the low side refrigerant pressure of the AC system. When the air temperature is close to freezing and the low side refrigerant pressure decreases to a trigger point, the switch disconnects the power supply to the compressor clutch to stop the compressor. When the air stream temperature subsequently increases and the refrigerant pressure rises to a second pressure setting, the compressor switch reconnects the clutch to a power supply and the compressor resumes operation. This method of operation continues to be used today due to the simplicity and low cost.

With the introduction of the microprocessor into the automotive industry, capacity control for the fixed displacement compressor gained a more precise and direct method. The temperature of the exit air from the evaporator is measured with a thermistor directly and communicated to a microprocessor either in the engine control module or in the air conditioning control head. The microprocessor compares the measured temperature with a pre-set control band, similar to a thermostat in the home air conditioning system, and makes the decision whether to turn on or off the compressor. For this compressor cycling scheme, typically there is a temperature set point and a hysteresis band. The temperature set point determines the level of temperature control, which is typically 1 to 2 degrees Celsius above the water freeze point. The hysteresis band typically is 1.5 degrees Celsius, and is designed to limit the frequency of the compressor cycling and the temperature variations at the discharge outlets.

The concepts of set point and hysteresis band also exist in the cycling pressure switch in the form of a low pressure set point for compressor disengagement and a second, higher pressure set point for compressor re-engagement. The difference between the two pressure set points is equivalent to the hysteresis band in the thermistor control scheme.

The considerations for designing the hysteresis band include the protection of the compressor clutch and the thermal comfort variation as perceived by the passengers. Too narrow of a hysteresis band causes the compressor to cycle at a higher frequency which may cause the clutch to wear out prematurely. Too wide a hysteresis band can lead to excessive temperature variations at the discharge outlets which can be an annoyance to the passengers in the car.

Recently, the cycling of the compressor gained a new application beyond the simple capacity control for freeze protection. With rising gasoline price and increased environmental concerns, more energy efficient air conditioning systems are being demanded by the vehicle manufacturers to help increase the overall fuel economy of vehicles. One popular method of increasing the energy efficiency of an AC system is to reduce the reheating of cooled air to a higher temperature to meet the discharge temperature requirement in the passenger compartment, either directly commanded by the passenger, which is the case with manually controlled air conditioning systems, or indirectly through the use of an automatic climate system.

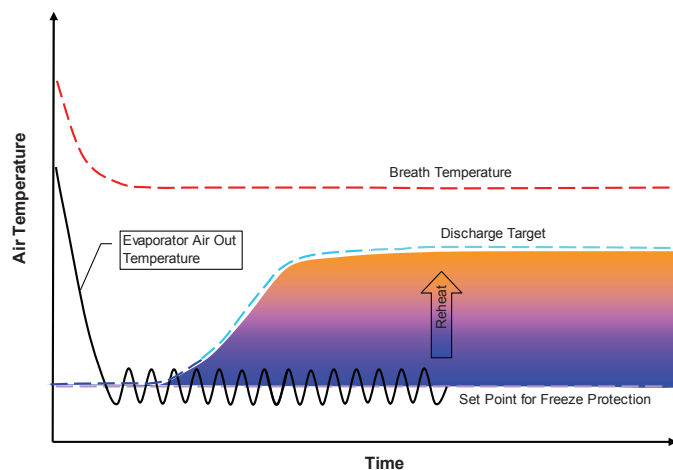


Fig. 1 Fixed Displacement Compressor Cycling

The reheat of air conditioned air to a higher discharge temperature (Figure 1) is typical in the automotive industry and has a long history - practically since the introduction of the air conditioning systems into automobiles. The main reason is that advanced compressor control method was not available beyond the simple pressure switch cycling control for freeze

protection. As a result, there are two fixed air temperature levels available to an air conditioning system: one temperature is provided by the refrigeration system which is maintained at slightly above the water freeze point and the second temperature is provided by the engine coolant. By taking a portion of the cooled air from the evaporator of the refrigeration system and feeding it through the heater supplied with engine coolant, the air temperature can be increased and subsequently remixed with the remaining stream of air from the evaporator to achieve any temperature bracketed by the water freeze temperature and the engine coolant temperature. The proportioning of air through the heater is accomplished by a device in the HVAC module known as the "mix door".

This method of temperature control through the mixing of cooled air and reheated air provides a system that is precise and responsive. The inefficiency of such a system in energy use is only highlighted recently as energy conservation and environmental protection became a new priority.

To reduce the reheat and, therefore, compressor energy consumption, the compressor is cycled to an elevated set point above that of the water freeze point. The general principle is to cool the air only as low as needed to meet the discharge temperature requirement. If the discharge temperature target is 10 degrees Celsius, there is no need to cool the air down to 2 degrees Celsius only to reheat it back up to 10 degrees Celsius. The compressor can be operated to the elevated temperature set point of 10 degrees Celsius with the air directly discharged to the passenger compartment without reheating. Of course, there is an upper limit as to how high one can raise the set point. Considerations must be given to humidity comfort in the passenger compartment and fogging risk at the windshield. A fixed level of dehumidification must be maintained to provide a comfortable and safe driving environment in the vehicle. Typically, energy efficiency AC systems limit the elevated temperature set point to around 10 degrees Celsius.

An alternative to cycling the fixed displacement compressors at an elevated set point for reheat reduction is to use the more sophisticated electronic variable compressors, whose control valve is capable of operating at any set point through varying the command current to the valve. Just as before, the compressor operates at a reduced displacement to meet an elevated temperature set point that is determined by the discharge temperature target, humidity comfort, and fogging risk at the windshield.

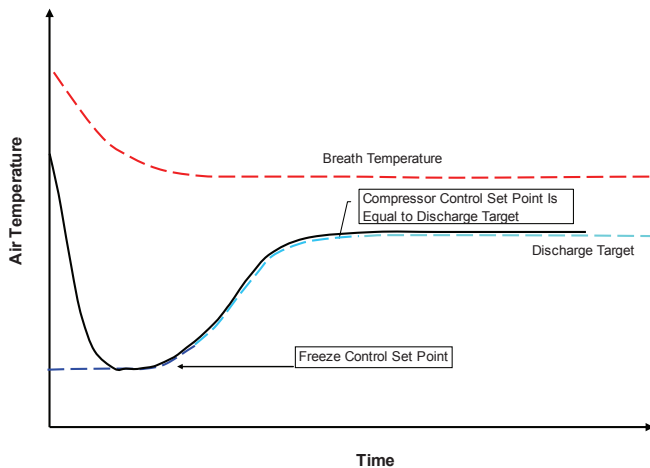


Fig. 2 Series Reheat Reduction with Electronic Variable Compressors

Figure 2 shows a typical discharge temperature history when the reheat reduction is achieved with an electronic variable compressor. As the discharge temperature change is achieved through active displacement control without cycling the compressor, the discharge temperature is distinctly smooth and lack of variation.

CYCLING OF PNEUMATIC VARIABLE COMPRESSOR FOR SERIES REHEAT REDUCTION

The pneumatic variable compressors (Figure 3) are designed to control the capacity of the compressor through varying the stroke of the compressor pistons [1]. Within a pneumatic variable compressor, the case pressure is varied between the suction pressure and the discharge pressure of the compressor by way of a 3-port valve. The case pressure works against the discharge pressure to modulate the stroke of the piston, thereby controlling the capacity of the compressor. Through the regulation of the compressor displacement, the suction pressure of the compressor is controlled to a near constant under various operating conditions which keeps the condensate on the evaporator from freezing.

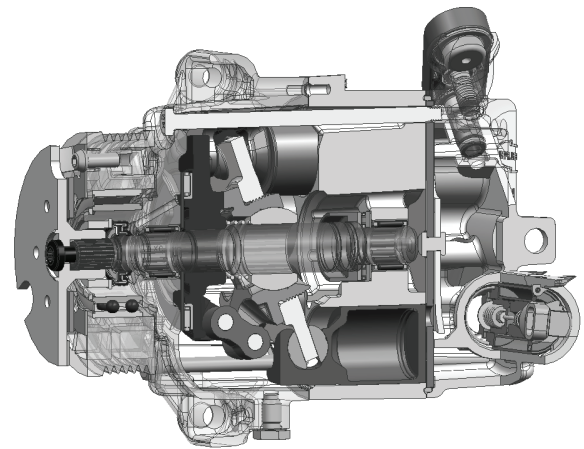


Fig. 3 Pneumatic Variable Displacement Compressor

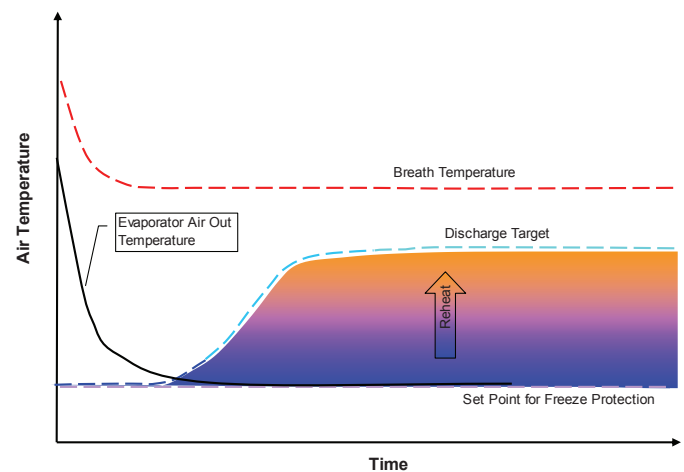


Fig. 4 Discharge Temperature by Mixing With Pneumatic Variable Compressor under Freeze Control

By design, a pneumatic variable compressor intrinsically controls to prevent evaporator freeze. The air temperature coming out of the evaporator is maintained slightly above the freeze point of water. The discharge temperature control is achieved using the same method of series reheating and mix door operation. Figure 4 shows a typical temperature control profile for an air conditioning system with a pneumatic compressor.

The pneumatic variable compressor is effective in that it eliminates the needs to cycle the compressor in order to prevent evaporator freeze. Higher energy efficiency than cycling fixed displacement compressor is achieved due to the steadier and continuous operation of the compressor [2]. However, under the new context of energy efficiency, the pneumatic compressor's internal control is incapable of regulating to a different control set point to allow series reheat reduction. The additional system efficiency associated with series reheat reduction appears to be out of reach for pneumatic variable compressors.

It is in this context that the Cycling Pneumatic Compressor concept was proposed. With this unconventional and counter-intuitive method of operating the pneumatic variable compressors [1, 2], higher energy efficiency AC operation can be achieved in several regards. First of all, for AC operations requiring freeze point control, either due to defogging or defrosting, continuous operation of the pneumatic compressor can be maintained under reduced compressor displacement, which delivers higher energy efficiency than the cycling fixed displacement compressors. As the discharge temperature target increases for reheat reduction, the compressor will still operate continuously for certain ambient conditions due to the control properties of the pneumatic valve. For other ambient conditions, it is possible that a combination of stroke reduction and lower frequency cycling work together to provide the elevated discharge temperature. It is commonly understood that cycling reduces the COP of the AC system [2, 3, 4, 5]. Consequently, higher energy efficiency operation is achieved than cycling the fixed displacement compressor alone.

Not intrinsic to cycling the pneumatic compressor, the cycling characteristics can be managed to decrease the cycling frequency so as not to affect compressor reliability on the one hand, and to achieve higher energy efficiency on the other.

CYCLING MANAGEMENT FOR THE PNEUMATIC VARIABLE COMPRESSORS

Whereas it is straight forward to cycle the pneumatic variable compressor for reheat reduction and higher energy efficiency, the management of the cycling characteristics to achieve enhanced energy efficiency and compressor reliability is a bit more intricate. Herein we present a method that is based on understanding the human comfort impact of the discharge temperature variations and the physical mechanism of the discharge temperature variations.

Figure 5 shows the working of the HVAC module. The blower draws either fresh air from the outside of the vehicle or recirculated air from the inside of the passenger compartment depending on the position of the air inlet door. Regardless of the source, the blower sends the air through the evaporator of the refrigeration system to be cooled to a lower temperature, typically slightly above the freeze point of water for basic systems, or elevated temperature for energy efficient systems.

The air coming out of the evaporator is split into two streams. One part of the airflow goes through a heater where it is warmed up by the engine coolant. The second part bypasses the heater. After the heater, the two streams of air are combined in a mixing chamber

ready to discharge into the passenger compartment to maintain comfort.

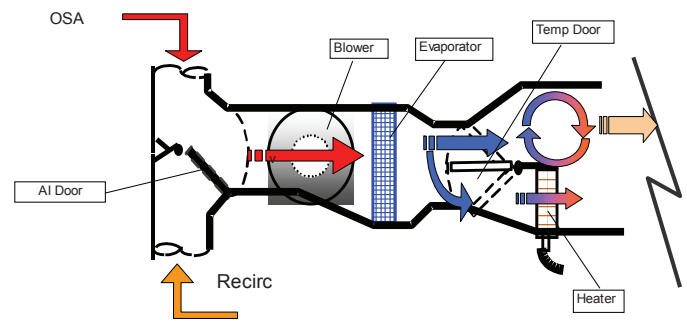


Fig. 5 Temperature Control in HVAC Module

HEATER OUTFLOW AIR TEMPERATURE CALCULATION

Assuming that the coolant temperature is known through the vehicle communication bus, and the evaporator air outflow temperature is measured by a thermistor, the outflow air temperature from the heater can be determined by the heater effectiveness map.

The heater effectiveness is the ratio of the air temperature rise through the heater over the maximum temperature difference available to the heater, as given in Equation (1):

$$\varepsilon = \frac{T_{htr} - T_{evp}}{T_{clt} - T_{evp}} \quad (1)$$

For a particular heater, the effectiveness is a function of the air flow rate and the coolant flow rate. Equation (2) describes this relationship:

$$\varepsilon = F(\dot{m}_{air}, \dot{m}_{clt}) \quad (2)$$

From Equations (1) and (2), the outflow air temperature from the heater can be determined by way of equation (3),

$$T_{htr} = \varepsilon(T_{clt} - T_{evp}) + T_{evp} \quad (3)$$

BULK DISCHARGE TEMPERATURE

The bulk discharge temperature from the HVAC module can be determined by mixing the two streams of air, that which goes through the heater and that which bypasses the heater. The percentage of the heater airflow is designated by a fractional flow function $f(\omega)$, where ω is the mixing door position spanning the range of Full Cold (0%) to Full Hot (100%). The formula for