A Review of Energy Efficiency Improvement Cycle effect Supermarket High Cooling and Low Power Refrigeration Systems

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ABSTRACT: Absorption refrigerators may provide a cooling effect using various energy resources in the system such as waste heat and renewable energy. However, supermarket refrigeration systems consume a substantial amount of energy. Taking for instance supermarket refrigeration systems they can account for up to 50-80% of the total energy consumption in the supermarket. Due to the thermal capacity made up by the refrigerated goods in the system there is a possibility for optimizing the power consumption by utilizing load is describes the dynamics and the modeling of a vapor compression refrigeration system needed for sufficiently realistic estimation of the power consumption and its minimization. This leads to a non-convex function with possibly multiple extrema. Such a function can not directly be optimized by standard methods and a qualitative analysis of the system's constraints is. The focus of the work is on estimating the power consumption of the system while estimating the cold reservoir temperatures as well. The models developed for each module as well as for the overall integrated system are validated by real data collected from a supermarket in. The results the model is able to estimate the actual electrical power consumption with a high fidelity. Moreover a simulation is introduced based on the produced model for demand-side in direct control of the power/energy consumption is presented by a simple simulation evaporator to the cargo within the container, sensing the temperature of the supply air, comparing the temperature of the supply air with a predetermined set-point temperature, and increasing the speed of the evaporator fan to a second speed faster than the first when the temperature of the supply air is lower than the predetermined set-point temperature to maintain the temperature of the supply air at the predetermined set-point temperature.

Keywords- Cycle effect, set-point, low power, condenser, optimization process

I. INTRODUCTION

In this study, a modified ecological function is presented for four-temperature-level absorption refrigerators, and an absorption refrigerator has been optimized using this function. An equivalent system was initially identified, followed by the application of the first and second laws of thermodynamics. Next, the optimization results were interpreted. The results of the optimization process, optimum A method for operating a refrigeration system for a container to pull down the temperature of cargo from ambient to a predetermined set-point temperature, the method comprising: operating a compressor of the refrigeration system at a first power to compress a refrigerant and direct the refrigerant through a condenser and an evaporator of the refrigeration system, wherein the compressor, condenser, and evaporator are connected in series initially operating an evaporator fan at a first speed to supply refrigerated supply air from the evaporator to the cargo within the container when the cargo is at ambient temperature;

sensing the temperature of the supply air; comparing the temperature of the supply air with the predetermined set-point temperature; and increasing the speed of the evaporator fan to a second speed faster than the first speed when the temperature of the supply air is lower than the predetermined set-point temperature to maintain the temperature of the supply air at the predetermined set-point temperature. The method of claim further comprising decreasing the speed of the evaporator fan from the second speed to a third speed slower than the second speed when the temperature of the supply air is higher than the predetermined set-point temperature to maintain the temperature of the supply air at the predetermined set-point temperature. The method of claim further comprising operating the compressor at a constant power when the fan operates at the first and second speeds. The method of claim further comprising operating the compressor at a second power lower than the first power when the supply air equals the predetermined set-point and the evaporator fan is at the second speed.

The method of claim wherein the first speed is a minimum speed and the second speed is a maximum speed. The method of claim wherein the first power is a maximum power. The method of claim further comprising driving the evaporator fan with a controllable evaporator fan motor. The method of claim further comprising controlling the evaporator fan motor by pulse width modulation (PWM) of the electric power supplied to the evaporator fan motor. The method of claim wherein driving the evaporator fan includes driving the evaporator fan with two-speed evaporator fan motor. The method of claim 1further comprising directing refrigerated supply air into the cargo container, circulating the air past the cargo, and returning the air as return air through the evaporator. A refrigeration system for a container to pull down the temperature of cargo from ambient to a predetermined set-point temperature, the system comprising: a compressor configured to operate at a first power to compress a refrigerant and direct the refrigerant through a condenser and an evaporator, wherein the compressor, condenser, and evaporator are connected in series; an evaporator fan configured to initially operate at a first speed to supply refrigerated supply air from the evaporator to the cargo within the container when the cargo is at ambient temperature's sensor configured to sense the temperature of the supply air; anda controller programmed to compare the temperature of the supply air with the predetermined set-point temperature, wherein the controller increases the speed of the evaporator fan to a second speed faster than the first speed when the temperature of the supply air is lower than the predetermined set-point temperature to maintain the temperature of the supply air at the predetermined set-point temperature. The system of claim 11, wherein the controller is programmed to decrease the speed of the evaporator fan from the second speed to a third speed slower than the second speed when the temperature of the supply air is higher than the predetermined set-point temperature to maintain the temperature of the supply air at the predetermined set-point temperature. The system of claim wherein the compressor is configured to operate at a constant power when the fan operates at the first and second speeds. The system of claim wherein the compressor is configured to operate at a second power lower than the first power when the supply air equals the predetermined set-point and the evaporator fan is at the second speed.

The system of claim, wherein the first speed of the evaporator fan is a minimum speed and the second speed is a maximum speed.

The system of claim wherein the first power of the compressor is a maximum power. The system of claim wherein a controllable evaporator fan motor drives the evaporator fan. The system of claim wherein the controller controls the fan motor by supplying pulse-width-modulated electric power to the fan motor.

The system of claim wherein the fan motor includes a two-speed evaporator fan motor. The system of claim wherein the evaporator fan is configured to direct refrigerated supply air into the cargo container, circulate the air past the cargo, and draw in the air as return air through the evaporator. A method for operating a refrigeration system for a container to pull down the temperature of cargo from ambient to a predetermined set-point temperature, the method comprising: operating a compressor of the refrigeration system at a first maximum power to compress a refrigerant and direct the refrigerant through a condenser and an evaporator of the refrigeration system, wherein the compressor, condenser, and evaporator are connected in series; initially operating an evaporator fan at a first minimum speed to supply refrigerated supply air from the evaporator to the cargo within the container when the cargo is at ambient temperature; sensing the temperature of the supply air; comparing the temperature of the supply air with the predetermined set-point temperature; increasing the speed of the evaporator fan to a second maximum speed faster than the first speed when the temperature of the supply air is lower than the predetermined set-point temperature to maintain the temperature of the supply air at the predetermined set-point temperature; decreasing the speed of the evaporator fan from the second speed to a third speed slower than the second speed when the temperature of the supply air is higher than the predetermined set-point temperature to maintain the temperature of the supply air at the predetermined set-point temperature; operating the compressor at a constant power when the fan operates at the first and second speeds; operating the compressor at a second power lower than the first power when the supply air equals the predetermined set-point and the evaporator fan is at the second speed; and directing the refrigerated supply air into the cargo container, circulating the air past the cargo, and returning the air as return air through the evaporator.In a refrigeration process heat is absorbed in an evaporator by evaporating a flow of liquid refrigerant at low pressure and temperature. Controlling the evaporator inlet valve and the compressor in such a way that a high degree of liquid filling in the evaporator is obtained at all compressor capacities ensures a high energy efficiency. The level of liquid filling is indirectly measured by the superheat. Introduction of variable speed compressors and electronic expansion valves enables the use of more sophisticated control algorithms, giving a higher degree of performance and just as important are capable of adapting to variety of systems. This paper proposes a novel method for superheat and capacity control of refrigeration systems; namely by controlling the superheat by the compressor speed and capacity by the refrigerant flow. A new low order nonlinear model of the evaporator is developed and used in a back stepping design of a nonlinear adaptive controller.

The stability of the proposed method is validated theoretically by Lyapunov analysis and experimental results show the performance of the system for a wide range of operating points. The method is compared to a conventional method based on a thermostatic superheat controller. Refrigeration systems are widely used as well in applications for private consumers as for the industry. Despite differences in size and number of components, the main construction with an expansion valve, an evaporator, a compressor and a condenser, remains to a considerable extent the same. Large parts of the same technological challenges are therefore encountered in both markets. In this paper we focus on a small water chiller, however the generality of the results applies to a larger family of so-called 1:1 systems, i.e. system with 1 evaporator and 1 compressor. Refrigeration and air conditioning, accounts for a huge part of the total global energy consumption, hence improving energy efficiency in these system can potentially lead to a tremendous reductions in the energy consumption. Optimizing the set-points of these systems has been proved to enable a substantial reduction in the power consumption in [1]. In [2] a method for on-line optimization of the set-points to minimize power consumption is presented. In a refrigeration system one of the key variables to control, which greatly affects the efficiency of the system, is the superheat. The superheat is used as an indirect measure of the liquid fraction of refrigerant in the evaporator. To utilize the potential of the evaporator to its maximum, the superheat should be kept as low as possible, i.e. the liquid fraction should be as high as possible. The superheat is traditionally controlled by adjusting the opening degree of the expansion valve. This is a common control strategy and examples can be found in e.g. [3] and [4]. Mechanical thermostatic expansions valves (TXV) is currently the preferred choice as expansion device in numerous applications. TXV's are relatively inexpensive and deliver a good control performance if designed and sized correctly. Designing and sizing TXV's is not always straight forward and once installed, the possibility of adjusting it to fit the specific application, is rather limited. Furthermore regarding production it requires many differentiated versions to fit the various applications. These shortcomings have opened for the introduction of electronic valves, which enable the use of more sophisticated control algorithms that potentially can overcome these difficulties. Controlling the superheat using standard SISO PID control, however often leads to poor performance, caused by mainly two major challenges. Firstly; the superheat is strongly coupled with the operation of the compressor. Neglecting this often leads to instability or the so-called hunting phenomena, see [5]. Secondly; the fact that the superheat acts highly nonlinear, depending on the point of operation and the evaporator design, limits the obtainable performance with standard PID controllers. Previous works by [6] and [7] have proved that gain scheduling is a way to handle gain variations. In [8] a new promising model based control designs that take the cross couplings between the (uncontrollable) compressor and the valve into account, has started to emerge.

By the introduction of variable speed compressors, an additional control variable that can be actively used has been introduced. [9] presents a new non-linear control strategy where the compressor is controlling the superheat and the valve is controlling cooling capacity. Recently this result has been improved in [10], where a new non-linear control strategy using a backstepping method based on Lyapunov theory is applied for improving stability. These techniques definitely an improved performance However they rely on a detail knowledge of specific system parameters, which are typically not available for a large part of the applications. Furthermore the focus on limiting the use of refrigerants (greenhouse gases) and increasing prizes on raw material have driven the introduction of new evaporator designs on a market, that is characterized by a low internal volume. Examples of such evaporators are micro channel and plate heat exchangers. Due to the low internal volume and thereby faster dynamics, these evaporators add to the above mentioned control challenges. To accommodate the control challenges introduced by these evaporator types and the requirements for adaptation this paper further develops the result presented in [10] with an adaptation routine to estimate unknown system specific parameters. With the new controller it is possible to make continuous control down to zero cooling power. Because the backstopping design is based on Lyapunov stability, the stability of the control and the adaptation can be guaranteed. By using this approach a nearly perfect decoupling between capacity and superheat temperature, for reasonable choice of gains in the controller, can be obtained.

II. EXPERIMENTS

On a test system show an excellent performance during startup as well as for variation of cooling capacity by step change of the compressor speed between minimum and maximum. The new controller is also compared to a conventional controller based on a thermostatic expansion valve (TXV) for controlling of the superheat. Refrigeration systems typically use a vapor compression cycle process to transfer heat from a cold reservoir (e.g. a cold storage room) to a hot reservoir, normally the surroundings. The main idea is to let a refrigerant circulate between two heat exchangers, i.e. an evaporator and a condenser. In the evaporator the refrigerant "absorbs" heat from the cold reservoir by[1] evaporation and "rejects" it in the condenser to the hot reservoir by condensation.

In order to establish the required heat transfer, the evaporation temperature (T_e) has to be lower than the temperature in the cold reservoir (Tcr) and the condensation temperature (Tc) has to be higher than the temperature in the hot reservoir (normally the surroundings T_a), i.e. $Te < Tcr$ and $Tc > Ta$.

The refrigerant has the property (along with other pure fluids and gases) that the saturation temperature (T_{sat}) uniquely depends on the pressure. At low pressure the corresponding saturation temperature is low and vice versa at high pressure. This property is exploited in the refrigeration cycle to obtain a low temperature in the evaporator and a high temperature in the condenser simply by controlling respectively the evaporating pressure (Pe) and the condensing pressure (Pc). Between the evaporator and the condenser is a compressor. The compressor compresses the low pressure refrigerant (Pe) from the outlet of the evaporator to a high pressure (Pc) at the inlet of the condenser, hereby circulating the refrigerant between the evaporator and the condenser. To uphold the pressure difference ($Pc > Pe$) an expansion valve is installed at the outlet of the condenser. The expansion valve is basically an adjustable nozzle that helps upholding a pressure difference. The test system is a simple refrigeration system with water circulating through the evaporator. The evaporator is a plate heat exchanger, i.e. an evaporator type with a low internal volume. The heat load on the system is maintained by an electrical water heater with an adjustable power supply for the heating element. The compressor, the evaporator fan and the condenser pump are equipped with variable speed drives so that the rotational speed can be adjusted continuously. The system is furthermore equipped with an electronic expansion valve that enables a continuous variable opening degree.

The system has temperature and pressure sensors on each side of the components in the refrigeration cycle. Mass flow meters measure the mass flow rates of refrigerant in the refrigeration cycle and water on the secondary side of the evaporator. Temperature sensors measure the inlet and outlet temperature of the secondary media on respectively the evaporator and the condenser. The applied power to the condenser fan and the compressor is measured. Finally the entire test system is located in a climate controlled room, such that the ambient temperature can be regulated. For data acquisition and control the toolbox for SIMULINK is used.

III. MODELING AND VERIFICATION

A detailed model for an evaporator is based on the conservation equations of mass, momentum and energy on the refrigerant, air and tube wall. This leads to a numerical solution of a set of differential equations discredited into a finite difference form, see [11]. This model gives very detailed information to the control designer comparable to the real system. This means that it is useful for testing controllers, but due to the high complexity not for design of new control principles. A simpler model may be obtained by using a so called moving boundary model for the time dependent two phase flows and by assuming that spatial variations in pressure are negligible, which means that the momentum equation is no longer necessary. The numerical solution may describe the system quite well and results are shown in [12] and [13]. The moving boundary model is very general and may be fitted to most evaporator types. By simplifying the moving boundary model further a very simple nonlinear model describing the dominating time "constant" and the nonlinear behavior between input and output .
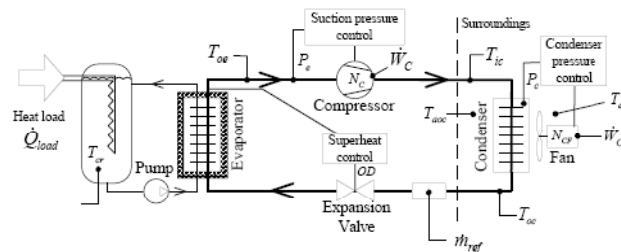

Fig. 1. Layout of the test refrigeration system including conventional control loops.

Supermarket refrigeration and refrigeration systems in general have been modeled for both analysis and control in several preceding publications. These are both concerned with the overall system [1-4] and the complex thermodynamics of the individual parts as evaporators and condensers [5-6]. However the focus in this paper is on describing the power consumption in supermarket refrigeration systems on a form that enables us to use optimization methods like Model Predictive Control (MPC)([7-8]) for minimizing the

total cost of running the system. This is not a completely new idea either. In [1] and [9] MPC is applied to refrigeration systems and in [4].
optimization is applied in order to utilize the daily variations to minimize power consumptions. The models used in such papers tend to be rather simple in their description of e.g. the work done in the compressor in order to make them fit into standard forms suitable for optimization and MPC.
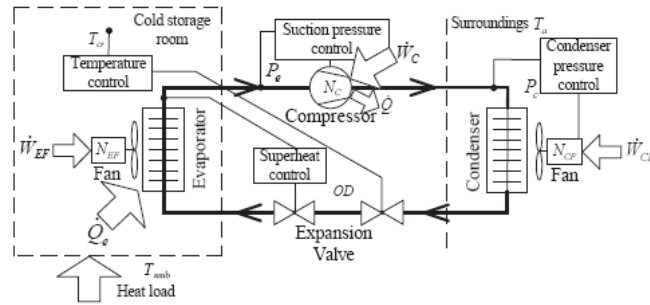
Fig. 2. Schematic layout of basic refrigeration system.

Thus, the current work focuses on choosing an abstraction level for the model such that sufficient simplicity can be obtained but with significantly improved accuracy with respect to energy consumption.

Most supermarket refrigeration systems utilize a vapor compression cycle where a refrigerant is circulated in a closed loop consisting of a compressor, an expansion valve and two heat exchangers, an evaporator in the cold storage room and a condenser/gas cooler located in the surroundings. When the refrigerant evaporates it absorbs heat from the cold reservoir which is rejected to the hot reservoir by condensation. In order to keep the refrigeration cycle flowing with the heat transfers as described here, the evaporation temperature (Te) has to be lower than the temperature in the cold reservoir (Tcr) and the condensation temperature has to be higher than the temperature at the hot reservoir (Ta). By inserting a compressor between the evaporator and the condenser the pressure, and thereby also the saturation temperature, of the refrigerant is increased such that the necessary temperature differences are achieved. Thus, low pressure refrigerant (Pe) from the outlet of the evaporator is compressed to a high pressure (Pc) at the inlet to the condenser. The expansion valve at the inlet to the evaporator upholds the pressure difference The setup is sketched with one cold storage room connected to the system. In most supermarket refrigeration systems [27] several cold storage rooms, e.g. display cases, are connected to a common compressor rack and condensing unit. Hence, all the individual display cases, which might have to satisfy different demands to temperatures, often sees the same evaporation temperature in a typical setup. However each unit has its own inlet valve for individual temperature control.

IV. CONCLUSIONS

In recent years, scroll compressors with VSD drives have gained an increased market share in small packaged air conditioning systems, due to improved efficiency and reliability brought about by advancements in material and manufacturing technology and optimised design. In the medium-capacity range, reciprocating, rotary and scroll compressors are being used with off-theshelf inverters. Research results have shown that open-drive compressors lead to better efficiency and allow smaller condensers to be fitted as the increased motor heat caused by the inverter losses is not rejected in the condenser. Over the past few years, the price of inverters has been steadily decreasing. This trend is attributed generally to improved design, increased production and the decrease in the price of power electronic devices. The reliability of inverters is also constantly improving, due to improved technology and the availability of better components. Space requirements are also decreasing, due to improved packaging, higher efficiency, more effective heat sinks and improved circuitry. The downward price trend and new technological developments are favourable for the increased use of VSD refrigeration in place of conventional refrigeration systems. There is also scope for achieving further energy savings by using high-efficiency motors if their present costs become competitive with standard induction-motors. The development of an optimum variable-speed refrigeration system is a function of several design factors and more research work is needed to fully understand the interaction of the components in an integrated VSD refrigeration system. Problems to overcome are the generation
of harmonics by the inverter, which affects both the supply and the motor, and the reduction ofthe motor efficiency at low speeds. Proper lubrication and cooling of the compressor at low speeds is also an important consideration. New developments in inverter technology, such as vector and fuzzy logic control, require further investigation as to their application to refrigeration systems. The energy-efficiency of optimized VSD refrigeration systems should also be investigated in different applications, such as low-temperature, medium-temperature and high-temperature refrigeration.

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