Chapter 6

Refrigeration System: Capacity Modulation Methods

Orhan Ekren

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.70433

Abstract

Energy conservation and reduction of the global warming effect become one of the most important subjects in the world. Since refrigeration system energy consumption is steadily increasing in overall energy consumption, this system is under research. Refrigeration systems are full of energy conservation that is having minimum energy consumption while satisfying the user's needs. Refrigeration system applications where the load may vary over a wide range, due to lighting, product loading, ambient weather variations, or other factors during operation, can be optimized by capacity modulation. There are many ways to achieve capacity modulation. This paper presents literature review of various capacity modulation methods which reduce the energy consumption of the refrigeration system and decrease CO_2 emission indirectly. In this paper, on/off control, digital scroll compressor, cylinder unloading, hot gas bypass, slide valve, multiple compressor, and variable speed capacity control methods are presented. In addition, electrical control techniques for the refrigeration capacity modulation applications are summarized.

Keywords: refrigeration capacity modulation, refrigeration system energy saving, reduce CO_2

1. Introduction

To meet the energy demand is the most critical problem in many countries because of steadily increasing energy consumption. If technologies and economic structures in the main world regions had remained at their 1990 level, in 2006 the world would have consumed 4.4 Gtoe more energy. The amount of electricity required to generate one unit of value added (electricity intensity) is increasing in most regions, especially in less industrialized regions in which the service sector is expanding rapidly, and in countries with air-conditioning (AC) requirements [1].

By 2050, it is expected that the world's energy supply will double today's demand [2]. Although some regions are moderate at this expected energy need since using more energy-efficient technologies, higher amount of primary energy will be needed in 2020. Energy from renewable sources will have an important impact on markets during the time period, but will not dominate any market. The use of nonconventional energy decreases in Asia, Latin America, and Africa because of a lack of effective government engagement [2]. Global CO_2 emissions from energy use were 34% higher in 2006 than in 1990. Trends in CO_2 emissions vary significantly between countries. Developing countries with high economic growth have doubled their CO_2 emissions, while Europe has nearly stabilized its emissions, partly because of climate change policies (**Figure 1**).

The inefficient use of electricity in refrigeration and air-conditioning systems is regarded as an indirect contributor to the emission of greenhouse gases to the atmosphere. These emissions can be decreased by more energy conversion, efficient refrigeration systems. In addition to this, it is known that the overall energy consumption of a refrigeration, air-conditioning, or heat pump system during its service life is a considerable cost factor and frequently is a multiple of the initial investment. Generally, refrigeration systems are designed for fixed capacity to achieve cooling capacity based on the maximum demand at the highest ambient temperature. The consequence is that the refrigeration system delivers high cooling capacity, is selected to overcome the worst condition, and needs to be cycled on and off when normal conditions occur. However, refrigeration systems are operated at partial loads in most of their life cycle. For example, chillers typically run 99% of the time at part-load (off-design) conditions [3]. Therefore, to evaluate the refrigeration systems' partial load efficiency is mandatory. The European Commission has published seasonal efficiency standard EN 14,825 taking into account part load conditions. Furthermore, Air-Conditioning, Heating and Refrigeration Institute (AHRI) has published AHRI standard 551–591/2011 which explains water chiller and heat pump performance rating. In this standard, a part-load chapter contains calculation methods and performance rating of partial load heating and cooling loads [3]. Capacity modulation which matches the system capacity to the load improves overall system efficiency at partial loads. In this chapter, the previous published researches on refrigeration system capacity control methods will be reviewed.

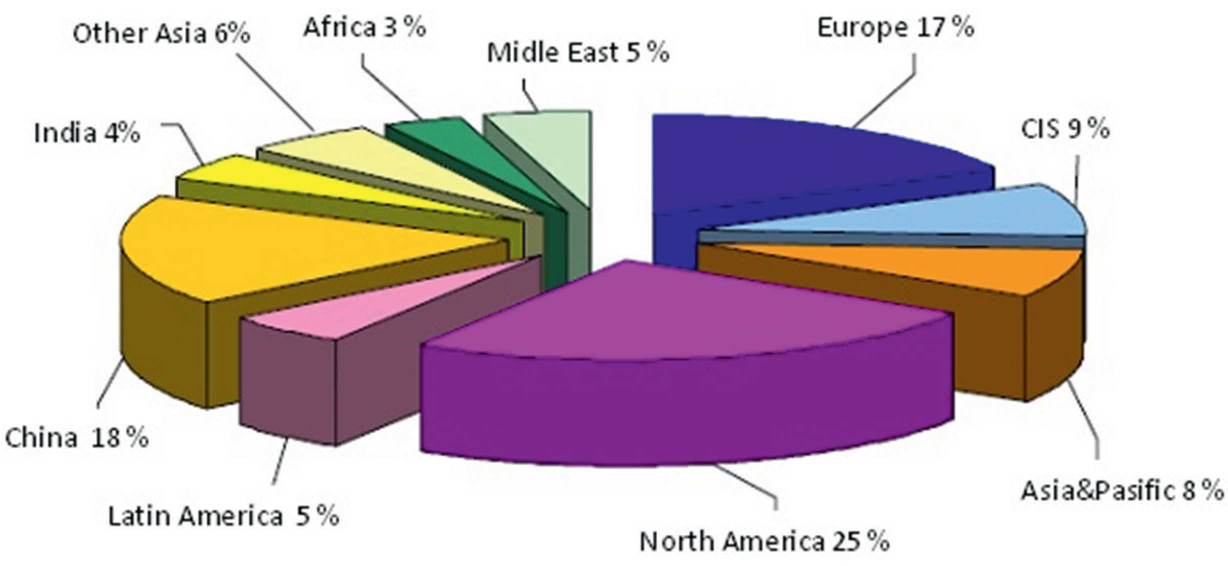

Figure 1. Distribution of world CO_2 emissions from energy use [2].

2. Capacity control methods

Refrigeration system applications where the load may vary over a wide range, due to lighting, product loading, ambient weather variations, or other factors during operation, can be optimized by capacity control. Capacity control can be employed either within or outside the compressor, but their basic function of varying the refrigerant flow rate in the cycle remains the same. Depending on the system, the requirements may change; whereby, the following criteria should be assessed carefully: control performance, energy consumption, costs of selected solution, operation reliability, application range of the compressor, minimum compressor running time, and loading of the power supply. The most common methods are on/off control, digital scroll compressor, cylinder unloading, hot gas bypass, slide valve, multiple compressor, and variable speed [4–7]. The review of capacity modulation methods and electrical control techniques is illustrated in **Table 1** as a summary. And, various types of capacity control methods based on compressor are shown in **Figure 2**.

No	Year	Author	Objective	Compressor	Control
Digital scroll capacity control					
1	2005	Hu and Yang [10]	Application of digital scroll compressor to multi-evaporator system	Scroll	PID
2	2005	Kan et al. [12]	Application of digital scroll for cold storage	Scroll	Conventional
3	2005	Zhou and Zhang [13]	Energy saving of digital scroll compressor	Scroll	Conventional
4	2006	Ye and Chen [14]	Digital scroll compressor in multi-evaporator system	Scroll	Conventional
5	2006	Jiang et.al. [11]	Digital scroll compressor in multi-evaporator system	Scroll	Conventional
6	2006	Qui and Qiu [15]	Accuracy temperature application of digital scroll	Scroll	Conventional
7	2006	Shi [16]	Compared digital scroll with inverter-driven compressor	Scroll	Conventional
8	2006	Ma and Sun [17]	Compared digital scroll with inverter-driven compressor	Scroll	Conventional
9	2007	Huang et al. [18]	Compared with digital scroll and conventional scroll	Scroll	Proportional on/off cycle
Cylinder unloading capacity control					
10	1974	Cawley and Pfarrer [19]	Two-speed and cylinder unloading comparison	Reciprocating	Conventional
11	1988	Wong and James [20]	Cylinder unloading and variable speed comparison	Reciprocating	Conventional
12	1989	Wong and Legg [21]	Economic evaluation	Reciprocating	Conventional
13	1996	Yaqub and Zubair [22]	Cylinder unloading and suction throttling comparison	Reciprocating	Conventional

No	Year	Author	Objective	Compressor	Control
14	2001	Yaqub and Zubair [23]	Cylinder unloading and other methods comparison	Reciprocating	Conventional
Hot gas bypass capacity control					
15	1995	Yaqub et al. [27]	Hot gas bypass thermodynamic analysis	Reciprocating	Conventional
16	2000	Yaqub et al. [28]	Liquid and gas injection to compressor suction side	Reciprocating	Conventional
17	2001	Tso et al. [29]	Hot gas bypass and suction modulation comparison with mathematical model	Reciprocating	Conventional
18	2005	Cho et al. [30]	Compared hot gas bypass and on/off capacity control	Rotary	Conventional
Slide valve capacity control					
19	2002	Reindl [32]	Slide valve capacity control fact	Screw	Conventional
Multiple compressor capacity control					
29	2003	Winandy and Cristian [33]	Two-parallel compressor control	Scroll	Conventional
Variable speed capacity control					
21	1979	Muir and Griffith [36]	Variable speed and on/off control for domestic A/C		Conventional
22	1981	Tassou et al. [37]	Energy conservation on capacity control		Conventional
23	1982	Tassou et al. [38]	Effect of capacity modulation on the performance		Conventional
24	1982	Lida et al. [43]	Experimental analysis of variable speed	Rotary	Conventional
25	1982	Itami et al. [44]	Compressor lubrication problem and mechanical effect of variable speed capacity control	Reciprocating rotary	Conventional
26	1983	Tassou et al. [4]	Comparison of performance capacity-controlled system		Conventional
27	1984	Janssen and Kruse [5]	Continuous and discontinuous capacity control		Conventional
28	1984	Tassou et al. [39]	Economic comparison of fixed- and two-speed heat pump		Conventional
29	1985	Senshu et al. [45]	Small-capacity heat pump application with different compressors	Scroll reciprocating	Conventional
30	1988	Shimma et al. [41]	Energy saving of inverters		Conventional
31	1988	McGovern [47]	Variable speed performance of two-cylinder compressor	Reciprocating (open type)	Conventional
32	1988	Ischii et al. [48]	Dynamic behavior of variable speed compressor	Scroll rotary	Conventional

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No	Year	Author	Objective	Compressor	Control
33	1988	Rice [57]	Energy saving of variable speed compressors		Conventional
34	1989	Zubair and Bahel [6]	Compressor capacity modulation schema		Conventional
35	1990	Ischii et al. [49]	Mechanical efficiency of variable speed compressor	Scroll	Conventional
36	1991	Tassou [40]	Dynamic performance of variable speed heat pump		Conventional
37	1992	Rice [58]	Performance analysis of reciprocating compressor	Reciprocating	Conventional
38	1992	Bose [61]	Variable frequency driver review	–	–
39	1994	Tassou and Qureshi [50]	Operating parameters for inverter-based variable speed rotary vane compressor	Rotary	Conventional
40	1996	Qureshi and Tassou [35]	Review of capacity control methods		Conventional
41	1997	Rasmussen [42]	Comparison of household single-phase fixed-speed and variable speed brushless DC motor drive	Reciprocating	Conventional
42	1998	Tassou and Qureshi [51]	Variable speed performance for different compressors	Reciprocating rotary	Conventional
43	2000	Ryska et al. [63]	Automotive application of variable speed	Automobile compressor	Conventional
44	2001	Park et al. [64]	Variable speed for multi-evaporator	Rotary	Conventional
45	2002	Saiz et al. [66]	Variable speed auto-compressor simulation	Automobile compressor	Conventional
46	2002	Park et al. [67]	Thermodynamic model for variable speed refrigeration system	Scroll	Conventional
47	2003	Cho et al. [54]	Inverter-driven compressor liquid injection	Scroll	Conventional
48	2003	Choi and Kim [65]	Variable speed for multi-evaporator	Scroll	Conventional
49	2004	Aprea et al. [55]	Effect of R22 R407C, R507, and R417A refrigerants for variable speed compressor	Reciprocating semi-hermetic	Conventional
50	2004	Aprea and Renno [68]	Modeling and experimental comparison of variable speed refrigeration system	Reciprocating	Conventional
51	2004	Shao et al. [69]	Variable speed compressor modeling and system simulation	Rotary	Conventional

No	Year	Author	Objective	Compressor	Control
52	2005	Kim and Kim [70]	Experimental study for artificial fault diagnosis variable speed refrigeration system	Reciprocating	Conventional
53	2006	Nasutin et al. [59]	Energy saving of variable speed and PID control		On/off P-PI-PD-PID
54	2007	Cho et al. [71]	CO_2 refrigerant for variable speed refrigeration system	Scroll	Conventional
55	2008	Cuevas and Lebrun [60]	Drawback of variable speed compressors	Scroll	Conventional
Electrical control applications					
56	1996	Cheung and Kamal [73]	Fuzzy and conventional control comparison for refrigeration system	Reciprocating	Fuzzy/PID
57	2003	Rahmati et al. [77]	Fuzzy and PID control comparison for HVAC systems		Fuzzy/PID
58	2004	Li et al. [80]	Fuzzy and PID control for automobile air-condition system	Automobile	Fuzzy/PID
59	2004	Aprea et al. [74]	Fuzzy control and on/off control comparison for refrigeration system	Reciprocating	On/ off-PID-fuzzy
60	2006	Aprea et al. [75]	Fuzzy-controlled and thermostat controlled-refrigeration system with EEV and TXV	Reciprocating	Fuzzy-on/off
61	2006	Aprea et al. [76]	Fuzzy control for chiller and heat pump variable speed driving methods	Scroll	Fuzzy/on/off
62	2006	Wang et al. [78]	PID, fuzzy, and fuzzy-PID control for HVAC system		Fuzzy/PID
63	2006	Navale [79]	Performance of fuzzy and PID control		Fuzzy/PID
64	2010	Ekren and Kucuka [72]	Performance of fuzzy control on compressor and electronic expansion valve	Scroll	Fuzzy

Table 1. Researches on capacity control methods and control applications.

2.1. On/off capacity control

The on/off capacity control is the simplest method adjusting the predetermined temperature (set point) using a thermostat. After the temperature reaches the set point, thermostat stops the compressor and circulating refrigerant in the cycle. Since the secondary fluid continues to circulate, the temperature of the water or air gradually raises. When the thermostat detects,

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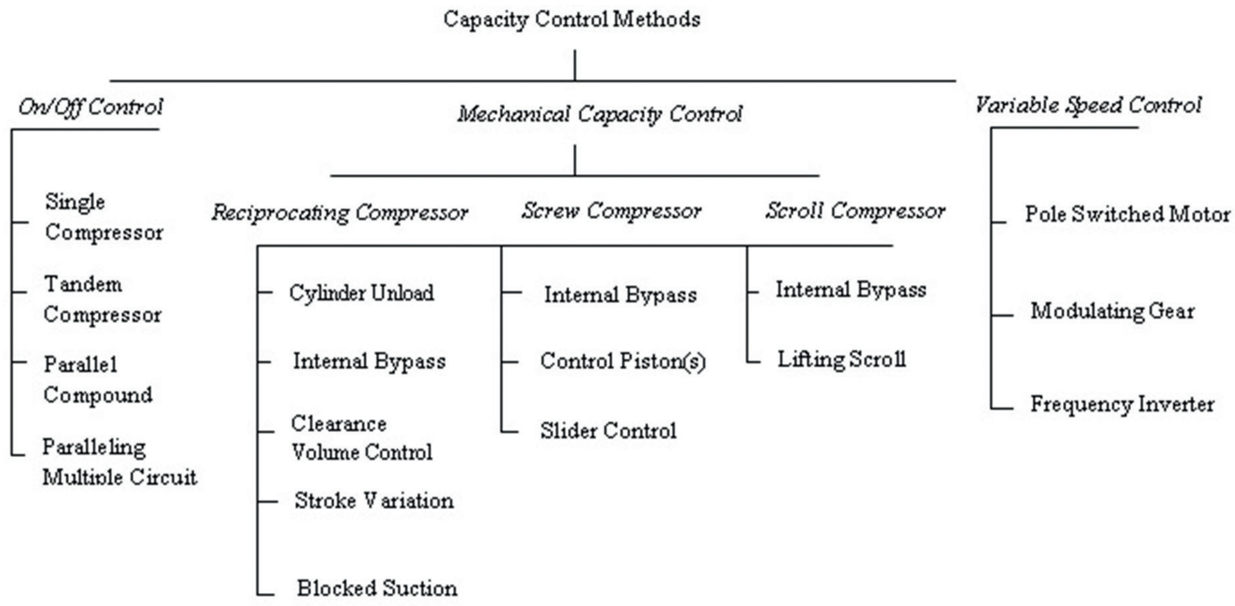

Figure 2. Capacity control methods [7].

this rise turns the compressor on. If the light-load conditions occur, this results on short cycling. Short cycling of the system reduces life of the compressor. In addition to that, the temperature of the secondary fluid fluctuates and uncomfortable conditions occur.

2.2. Digital scroll capacity control

In this method, scrolls force to separate and compression of refrigerant stops. This modulates refrigerant flow without changing or stopping the compressor motor. The separation of the scrolls is realized by using an external solenoid valve; also, there is a bypass connection line between the discharge chamber and the intake gas. The upper scrolls can separate from the bottom scroll by 1 mm vertically. A piston is fixed to the top of the upper scroll and lifts up the upper scroll when it moves up. There is a modulation chamber at the top of the piston that is connected to the discharge pressure through a bleed hole. An external solenoid valve connects the modulation chamber with the suction side pressure. If the solenoid valve is closed, the scrolls operate as a classical scroll compressor. If the solenoid is opened, the discharge chamber and intake gas pressure connect each other and decrease the discharge pressure. This leads to less pressure holding the piston down, thereby causing the piston to shift upward, which in turn lifts the upper scroll. This action separates the scrolls and results in no mass flow through the scrolls. De-energized external solenoid valve again loads the compressor fully, and the compression is resumed (**Figure 3**) [8].

During the loaded state, the compressor operates like a standard scroll and delivers full capacity and mass flow. However, during the unloaded state, there is no capacity and no mass flow through the compressor. The scrolls are separated in a periodic cycle (20 seconds) to obtain a time-averaged compressor capacity based on the ratio of loading and unloading times. This allows the digital scroll to achieve infinite capacity modulation between 10 and 100%.

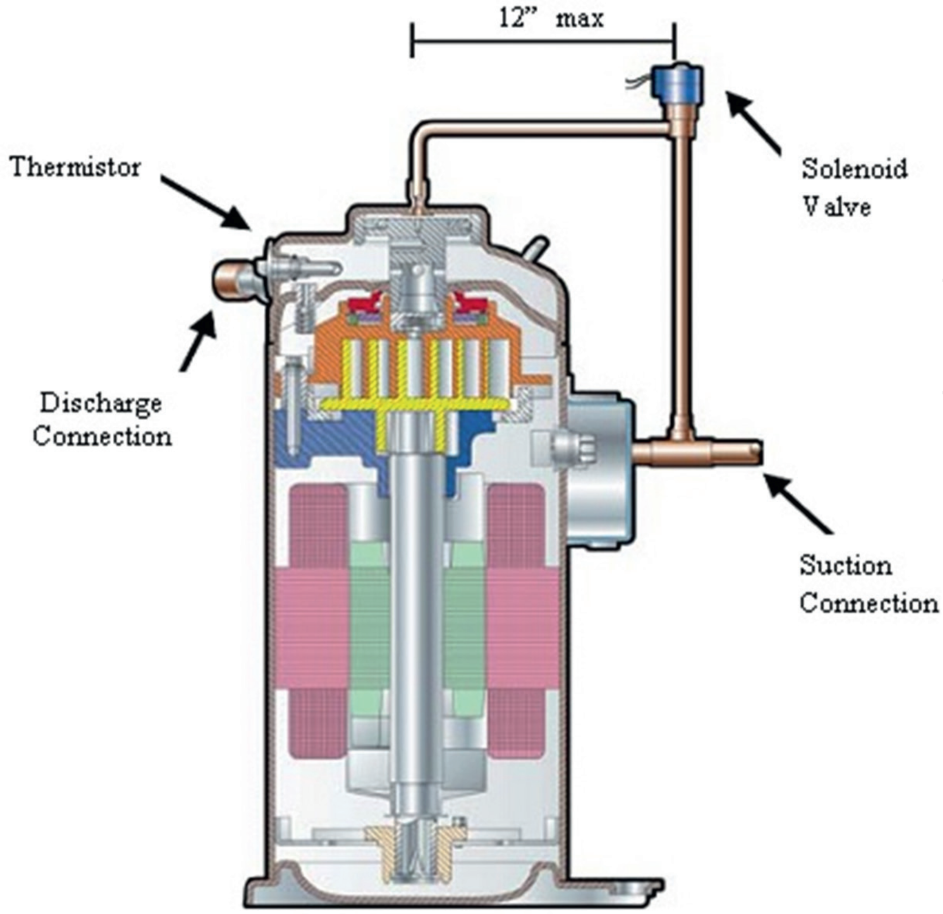

Figure 3. Digital scroll piping.

For example, 20-second cycle and the solenoid are de-energized for 16 seconds and then energized for 4 seconds; the resulting capacity will be 80% [8, 9]. This method provides very wide capacity range with continuous modulation, high efficiency, and very tight temperature control. But higher initial cost is the disadvantage of these methods compared to hot gas bypass method. Also, variable speed and digital scroll capacity controls are compared, and they give very close capacity modulation results [9].

The application of digital scroll compressor in multi-type air-conditioning system was introduced by Hu and Yang [10]. The authors reported the results from the development and performance testing of a cost-effective, energy-efficient, multi-type air-conditioner. In this system, about 75% reduction in power consumption was observed, while a partial load of 17% is occurred. The capacity modulation range of the system is in the range of 17–100%; on the other hand, an AC variable frequency control system has a range between 48 and 104%. In this method, system cost is 20% cheaper than an AC inverter. There are many studies on digital scroll; here, I will give summary of them such as Jiang et al. [11] discussed the control of digital compressor applied in multi-type air-conditioning system. Kan et al. [12] analyzed the application of digital scroll compressor in cold storage container. Zhou and Zhang [13] and Ye and Chen [14] studied the energy saving of digital scroll compressor. Qiu and Qiu [15] discussed the application of digital scroll compressor in high-accuracy constant temperature and humidity air-conditioning. Analysis and comparison between digital scroll and inverter technology were studied by Shi [16] and Ma and Sun [17].

Huang et al. [18] conducted an experimental study on operation characteristics with variable air volume under refrigerating and heating condition of ducted air-conditioning (AC) unit with digital scroll compressor and conventional scroll compressor. The effects of air volume on the refrigerating (heating) capacity, input power, EER (COP), outlet temperature, discharge pressure, discharge temperature, and suction pressure were studied. As a result, the authors reached that the unit with digital scroll compressor was well adapted to the variable air volume system and good for the economical and reliable operation of the ducted AC unit.

2.3. Cylinder unloading capacity control

Capacity control also can be occurred through reciprocating compressor's cylinder unloading. The cylinder unloading capacity control method (suction valve unloading method) works by lifting the suction valves of some cylinders to the open position. A thermostat (or pressure transducer) energizes a solenoid (or solenoids if there are multiple cylinders in the compressor) that forces the suction valve to stay open. The gas cannot be compressed within the open cylinders, which results a drop in refrigeration capacity. In order to prevent overheating of the compressor, a thermostatic expansion valve should be installed to provide cooling to the compressor suction gas. This capacity reduction is then followed by hot gas bypass. Their construction is relatively low in cost, but they usually require a multicylinder compressor. The achievable capacity graduations depend on the constructional design. With 4, 6, and 8 cylinder compressors, it is usual to operate two cylinders per load stage, which permits graduations of (25)–50–(75)–100% or 33–66–100% [7].

Cawley and Pfarrer [19] have realized a comparative study regarding the part-load efficiency of two-speed compressors using compressor unloading capacity modulation. They found that 49% higher energy efficiency ratio (EER) could be reached using a two-speed compressor instead of a cylinder unloaded compressor. Lower frictional losses at half speed of the two-speed compressor reduce power input. Wong and James [20] resulted that variable compressor speed control is more efficient compared to cylinder unloading control. By using variable speed operation, volumetric efficiency and isentropic efficiency as well as coefficient of performance (COP) are increased at lower compressor speed. On the other hand, cylinder unloading control reduces isentropic efficiency and COP. Wong and Legg [21] also studied the economic benefits of a variable speed compressor in another work. It was shown that variable speed control leads to reduced energy consumption, but for intermittent operation, it may not be economically viable due to the high capital cost of the inverter.

The later study related with cylinder unloading method is investigated by Yaqub and Zubair [22]. They studied cylinder unloading and suction gas throttling schemes to reduce the capacity of refrigeration and air-conditioning systems at reduced load. In the first scheme, an unloaded valve was used to unload one or more cylinders at part-load conditions. The mass flow rate of refrigerant reduces by unloading of cylinders; therefore, the system capacity reduces. A throttling valve is needed before the compressor to reduce the mass flow rate through the compressor. It was found that the cylinder-unloading method was the best and had the highest COP and minimum irreversible losses at any system capacity.

In another study, Yaqub and Zubair [23] investigated three different capacity control schemes. He compared cylinder unloading scheme with hot gas bypass and compressor suction throttling. These schemes are investigated for HFC-134a by considering finite size of the components that are used in the refrigeration systems. A comparative study was performed among these schemes in terms of the system coefficient of performance (COP), the operating temperatures, and percentage of refrigerant mass fraction as a function of the percentage of full-load system capacity. The models consider the finite-temperature difference in the heat exchangers, thus allowing the variations in the condenser and evaporator temperatures with respect to capacity and external fluid inlet temperatures.

2.4. Hot gas bypass capacity control

Hot gas bypass is a method that modulates refrigerant flow by bypassing some of the high pressure refrigerant gas (hot gas) discharged from the compressor back to the suction line without going through the evaporator, and the gas does any cooling. The capacity of reciprocating and centrifugal compressors can also be controlled by this method. Some applications use two or more methods for smoother switching and better control such as unloading in conjunction with hot gas bypass. Extra valves and piping are required for this capacity control, and capacity can be quickly adjusted by opening or closing a valve, but the number of capacity steps is finite. It may not prove precise and smooth temperature control [8, 24]. Suction pressures below the compressor designed limit are prevented because low suction densities result in poor compressor cooling. Therefore, hot gas bypasses into the systems' low pressure side.

Hot gas can be injected into different locations: the first one is the evaporator inlet after the distributor nozzle but before the distributor tubes, and the second one is the suction line [25, 26].

Bypass into evaporator inlet: on single evaporator and close connected systems, it is generally possible to introduce the hot gas into the evaporator inlet immediately after the expansion valve. Bypassing at the evaporator inlet results an artificial cooling load. Since the thermostatic expansion valve meters required refrigerant feed to maintain preset superheating value, the refrigerant returns to the compressor at normal operating temperatures and prevents motor heating problem. High flow velocity helps the oil returning in the evaporator [25].

Bypass into suction line: in this method, multiple evaporators are connected to a compressor, or if the condensing unit is remote from the evaporator, it may be necessary to bypass hot gas into the refrigerant suction line. Suction pressures can be controlled with this method. To meter liquid refrigerant into the suction line is required in order to keep the temperature of the refrigerant gas entering to the compressor within allowable limits. If this method is used by passed hot gas and liquid refrigerant must be mixed at correct amount in order to provide mixed gas into the compressor at desired temperature. For this purpose a mixing chamber is recommended. A suction line accumulator can serve as a mixing chamber and also protects the compressor from liquid flood back [25].

The first study related with this method is investigated by Yaqub et al. [27], and in this study, an automatic hot gas bypass technique is applied to reduce the capacity of refrigeration and air-conditioning systems at part-load conditions. Hot gas bypass valve sends high pressure refrigerant into the suction port. They discussed three hot-gas bypass schemes for HFC-134a and analyzed on the basis of the first and second laws of thermodynamics. Second-law-based thermodynamic analysis indicated that the total irreversible losses of the bypass valve increase substantially, as the capacity decreases. In another study, Yaqub et al. [28] investigated capacity control of a vapor-compression refrigeration system by injecting hot gas and liquid refrigerant into the suction side of the compressor. It was demonstrated that the compressor discharge temperatures increase significantly, when the hot gas from the compressor discharge is extracted and injected (without any liquid injection) directly into the suction side of the compressor.

Besides, Tso et al. [29] compared hot gas bypass control and suction modulation in refrigerated shipping containers by using mathematical model. They studied to analyze compressor power draw, coefficient of performance, and the sensible heat factor of evaporator against the container load. They resulted that suction modulation method is more energy efficient than hot gas bypass.

The performance of the showcase refrigeration system with three evaporators was measured during on/off cycling and hot gas bypass defrost by Cho et al. [30]. Based on the test results, the effects of off-period in the on/off cycling and electronic expansion valve (EEV) opening in the hot gas bypass defrosting cycle on the performance of showcase system were analyzed.

2.5. Slide valve capacity control

The slider control allows an adaptation of the compressor displacement to the power requirement by shifting the start of the compression process through an axial slide of the control slider. At the same time, the outlet window is adapted to the newly developing displacement in this series. Rotary-screw compressors use slide valves to adjust the necessary refrigeration capacity at partial loads by permitting the equipment to reduce the total volume of refrigerant compressed within the housing. The slide valve modulates compressor capacity between 25% to 100% range by 25% steps. The suction gas flow is measured in order to get the cooling capacity, and the volume ratio of the compressor is defined by the position of the suction contour and the size of the discharge port [31]. According to Reindl [32] one of the most common capacity control methods is capacity control slide valve for screw compressor. As the volume of refrigerant vapor to undergo compression is reduced, the compressor's capacity is reduced, and the effective volume ratio of the compressor also decreases.

2.6. Multiple compressor capacity control

Refrigeration system capacity can be modulated by using multiple refrigeration circuits or by using multiple compressors in single-circuit systems. Under partial load conditions, the compressors may be cycled in and out of service as required as well as providing a level of redundancy in the event one of the compressors should fail. Oil equalization is needed for these kinds of compressors. One of the least expensive forms of modulation, reliability, can be seen as advantages of the multiple compressor capacity control. On the other hand, multiple compressor capacity provides finite number of capacity steps and limited efficiency gains. For example, in a 40 hp system requiring 25 hp of output at a given time, the system must operate at 30 hp output. Also, precise and smooth temperature and humidity control may not obtainable, because of the capacity modulation step [7, 8].

Winandy and Cridtian [33] realized a study regarding multiple compressors in which the condensing units have tandem scroll compressors. The main drawback on this configuration is oil returning to the compressor which is a serious trouble especially at part load.

According to ASHRAE [34], the gas velocities and piping geometry are the most important matter in multiple compressor control method because of ensuring adequate oil return. When working at part load, some modifications may be needed to ensure proper oil return. In addition, it is recommended that to separate the refrigerant circuits while parallel operating of compressors, however, this configuration is not always possible and does not give the same operational advantage at part load.

2.7. Variable speed capacity control

Variable speed control can be realized in different ways to regulate the speed of the compressor motor such as electronic variable frequency drives. Variable frequency drives (VFD) are also known as adjustable-frequency drives (AFD), variable speed drives (VSD), AC drives, micro-drives, or inverter drives. Compressor rotational speed can be varied to match the system's changing requirement for refrigeration capacity of a variable speed drive. Variable speed capacity control studies contain mechanical, electrical fact about compressor and other equipments. Primary studies on variable speed refrigeration systems were related with the theoretical analysis of the concept of variable speed capacity control and the investigation of the problems associated with the mechanical design of the system [35].

The following studies are related with main benefits and facts of the variable speed capacity control methods. Muir and Griffith [36] investigated different aspects of capacity modulation methods for refrigeration and domestic air-conditioning systems using the seasonal energy efficiency ratio (SEER). This method compares the seasonal efficiency of systems, taking into consideration the effects of on/off cycling and steady-state efficiency at several outdoor temperatures. The analysis showed that application of capacity modulation and significant energy savings can be possible due to decrease in on/off cycling losses and improvements in steady-state efficiency at partial loads.

Tassou et al. [4, 37–40] investigated the most fact of the variable speed capacity control methods, and they focused on the capacity modulation of domestic size of heat pumps. Energy conservation via capacity control and performance comparison with conventional systems, effects of capacity modulation, mathematical modeling of variable speed systems, part load, and dynamic performance analysis of heat pumps are the important issues investigated. The investigations showed that variable speed control could achieve a 15% improvement in energy conversion efficiency, compared to a conventional system. It was also found that superheat control with a thermostatic expansion valve was unsatisfactory during part-load operation, and it was suggested that the problem could be effectively overcome by employing a microprocessor-controlled motorized expansion valve.

The study of Shimma et al. [41] is related with the evaluation of energy savings by using inverters in air-conditioners. According to the authors, the maximum energy savings and better system performance could be achieved by employing better control methods. Furthermore, improving the performance of individual components in the air-conditioning system could provide better system performance. The capacity-controlled system resulted in a reduction of the room temperature fluctuations to 50% of those for the conventional on-/off-controlled system. The authors pointed out various problems such as improvements in the refrigerant throttling mechanism, adoption of more effective noise suppression techniques (which is important to reduce radio wave interference noise and harmonic noise generated by the inverter), enhancement of the reliability and performance of inverter, and improvements in the overall system design to reduce noise at high-frequency operation and to overcome vibration problems at low-frequency operation.

According to Rasmussen [42], household refrigerators are usually thermostat (on/off)-controlled, constant speed, and mostly they have a single-phase induction motor as compressor drive. The author represents results of a prototype refrigerator using variable speed, three-phase, brushless DC motor drive. Test results of the motor and drive efficiency are presented; also, motor construction are described.

Also, different types of compressors are investigated in variable speed capacity control system by different authors. Papers dealing with rotary compressor were studied by Lida et al. [43]. On a heat pump equipped with a 4 hp (3 kW) hermetic rotary compressor, experimental studies are realized. They found that the practical limits for compressor speed variation were between 25 and 75 Hz. The results indicated improvements in EER with the inverter-driven compressor compared to a fixed-speed system. Cost and SEER analyses showed a 20% increase in the total cost for the inverter-controlled system and between 20 and 26% energy savings over the constant single capacity system. Other advantages identified for variable speed control over fixed-speed systems included accurate temperature control, system soft-start capabilities, and low-noise operation at reduced loads.

In the same year, Itami et al. [44] studied the performance and reliability factor of reciprocating and rotary compressors (frequency controlled). For the different type of compressor, modifications were suggested. For example, with the reciprocating compressor, a two-stage oil pump was used over the low-frequency range to ensure proper lubrication. For the rotary compressor, a liquid injection system was used to protect from overheating. Also, a disc mechanism was adopted to prevent increased amounts of discharge oil at the higher operating-frequency range. While the operating frequency was increased, the rotary compressor showed improvements in the volumetric and motor efficiencies; on the other hand, the reciprocating compressor shows improvement in mechanical and compression efficiencies, while the operating frequency was decreased. About 20–40% improvement in the SEER was reported with the variable speed air-conditioner compared to the conventional on/off-controlled system. In another related study, Senshu et al. [45] investigated on a small-capacity heat pump using a scroll compressor. This system showed a 30% improvement in annual performance efficiency compared with the conventional reciprocating compressor. It is important that the EER of the inverter-driven heat pump at nominal load conditions was found less than a fixed-speed system, due to the inverter losses. In an ASHRAE research, project (RP-409) analyzed a large chiller operating with a variable speed controlled centrifugal compressor [46]. The results showed that variable speed control provides a 1.5% reduction in the compressor power consumption at maximum load and about 40% reduction at minimum load.

McGovern [47] investigated the performance of a two-cylinder and open-type reciprocating compressor with the speed range between 300 and 900 rpm. Different performance parameters, such as mass flow rate, shaft power, and compressor discharge gas temperature, showed a linear increase for the tested speed range; on the other hand, the volumetric efficiency was found to remain almost constant at 66% of the given speed range. The variation of mechanical efficiency with speed was 92–94% at the speed increased from 300 to 900 rpm, respectively.

Other authors studied with compressor were Ischii et al. [48, 49]. The authors compared mechanical efficiency and dynamic performance of scroll compressors with rolling piston rotary compressors. They found that the scroll compressors exhibited better vibration than the rolling piston rotary compressor; on the other hand, they exhibited lower mechanical efficiency. They reported that the mechanical efficiency of scroll compressors could be improved via design optimization.

Another study dealing with compressors was investigated by Tassou and Qureshi [50]. This study contains application of inverter-based variable speed drives for positive displacement rotary vane-type refrigeration compressors. The effects of the inverter on a number of operating parameters such as harmonic currents and voltages, power consumption and power factor, starting current, and overall system efficiency were investigated. Results showed that inverter may cause a reduction in the power factor and in the overall efficiency of the driver. According to results, variable speed operation of a rotary vane compressor can provide better temperature control and quick response to disturbances and changes in load.

Tassou and Qureshi [51] studied on positive displacement refrigeration compressors' variable speed capacity modulation. Compressors tested include an open-type reciprocating, a semi-hermetic reciprocating, and an open-type rotary vane. The results indicate that all three compressors were designed for maximum efficiency at nominal speed and all three compressors when operated at variable speed offer energy savings compared to their fixed-speed counterparts. Also, at constant head pressure, only the open-type compressor exhibited an improvement in the COP at reduced speeds. With variable head pressure control, all three compressors showed an increase in the COP with a reduction in speed. The analysis showed the open-type reciprocating compressor to be the most efficient system offering 12% savings when operating in a temperate climate and 24% savings when operating in a warm climate.

Rarely, gas and liquid refrigerant injection to the compressor is done. Gas injection is applied to increase compressor capacity and to save energy. Since more refrigerant passes through the condenser than through the evaporator compressor, capacity may increase some. Also, liquid refrigerant is injected to the compressor to decrease high discharge refrigerant temperatures which chemically degrade oil and refrigerant and cause

http://dx.doi.org/10.5772/intechopen.70433

mechanical failure. High cost and additional component requirement are disadvantages of the gas and liquid injection system; also, liquid injection may cause slugging problem in the compressor [52, 53]. Cho et al. [54] applied the refrigerant injection to the variable speed compressor and measured performance of a liquid refrigerant injected inverter-driven scroll compressor with respect to variation of compressor frequency, injection pressure, and injection location. Furthermore, the influence of liquid injection on the performance was presented as a function of operating parameters and injection location. Results were compared with the non-injection case. For high frequency at a given injection ratio, the injection at 180°, for an injection angle at an injection port, yielded slightly better performance of the compressor as compared to that at 90°. It was found that liquid injection under high frequency was very effective, but injection under low frequency resulted some negative effects in the point-of-view compressor power, capacity, and adiabatic efficiency because of higher leakage through the scrolls.

Aprea et al. [55] presented a research dealing with compressors too. In this study, an experimental analysis has been realized, and they compared energetic performance of variable speed compressor and on/off control controlled with a classical thermostat. They used a semi-hermetic reciprocating compressor working with the refrigerants R22, R507, and R407C. The compressor was designed for a nominal frequency of 50 Hz, but they tested it in the range 30–50 Hz. The results showed that, using the R407C, an average of an electric energy consumption about 12% smaller when an inverter was employed to control the compressor refrigeration capacity instead of the thermostatic control is possible. So the R407C confirms its superiority in comparison with the R417A and R507; only the R22 shows a better performance.

Except this, energy-saving potential of the capacity control methods is studied by some researches. A feasibility and design study of a variable capacity refrigeration system was carried out by the *Energy Efficiency Demonstration Scheme* on behalf of the Department of Energy [56]. A commercially available variable speed compressor was monitored in a supermarket refrigerator. In this study at first, a conventional system was installed and then converted to variable speed for comparison. The results showed 56% power saving with high temperature (dairy applications) and a 30% saving with low temperature (frozen food applications). The energy savings achieved were attributed mainly to variable speed control and fully floating head pressure.

Rice [57, 58] studied on a heat pump, and he reported 27% energy savings for a modulating heat pump system. In that study reduced cycling losses, heat-exchanger unloading, reduced frosting/defrosting losses, and reduced backup heating were taken into account. He found that higher motor-slip losses and distorted inverter waveform decreased the conventional three-phase induction motor efficiency up to 20%, and he suggested that these losses could be reduced by a permanent magnet and electronically commutated motor-inverter combination.

Nasutin et al. [59] studied on the potential of energy saving of a variable speed compressor. The main aim of the system is to provide thermal comfort for application in air-conditioning system and to enhance load-matching capability of the system. In this study a constant speed system was retrofitted using an inverter and a proportional-integral-derivative (PID) controller used. As a result, energy saving for the system was estimated about 25.3% at a temperature of 22°C via PID controllers.

Recently, Cuevas and Lebrun [60] introduced an experimental study dealing with drawbacks of variable speed compressors which are concerning the inverter efficiency, the effect of the inverter on the induction motor, and the effect of variable speed on the compressor isentropic and volumetric efficiencies. It was observed that the inverter efficiency varies between 95 and 98% for compressor electrical power varying between 1.5 and 6.5 kW and that compressor efficiencies are not enormously influenced by compressor supply frequency. When the compressor speed is 75 Hz, a slight degradation occurs because of the electromechanical losses. These losses increase with compressor speed. A maximal isentropic efficiency of 0.65 for a pressure ratio of the order of 2.2 was obtained. The experimental results obtained at 50 Hz were used to identify six parameters of a semi-empirical model which was then used to simulate the different tests developed at different compressor speeds. The simulated results were in very good agreement with those measured. The results showed that motor losses induced by the inverter are negligible.

Studies related with VFD are important for variable speed capacity control method. A comprehensive technology review of the application of power electronics was given by Bose [61]. According to author currently available VFD systems can be classified into three basic inverter types: the six-step voltage inverter (VSI), the six-step current inverter (CSI), and the pulse-width-modulated voltage source inverter (PWM). A report published by the Energy Efficiency Office [62] compares typical efficiencies of six VFD types of different ratings. The PWM inverter shows a slightly better efficiency over VSI and CSI.

In addition, automotive refrigeration system, multi-evaporator, system modeling, fault diagnosis, and CO_2 refrigerant were applied to variable speed compressor. These subjects are explained below, respectively.

Ryska et al. [63] presented that a new evaluation method allows the overall cooling performance improvement for truck or bus at different engine speeds and driving styles. This method was demonstrated in two refrigeration units.

Park et al. [64] investigated multi-type inverter air-conditioner with a variable speed rotary compressor and an electronic expansion valve. Performance of the system was analyzed with different operating frequencies of the compressor, different cooling loads and cooling load fraction between rooms. The optimum opening amount of the electric expansion valve (EEV) was also calculated.

Choi and Kim [65] measured performance of an inverter-driven multi-air-conditioner with two indoor units using electronic expansion valves (EEV). For the performance varying indoor loads, EEV opening and scroll compressor speed have been investigated. According to the experimental results, the author suggested around 4°C superheats for both indoor units by using EEV also as the compressor speed needs to be adjusted to provide optimum cooling capacity for the indoor units.

Saiz et al. [66] have developed a steady-state computer simulation model for refrigeration circuits of automobile air-conditioning systems. The simulation model includes a variable capacity compressor and a thermostatic expansion valve in addition to the evaporator and micro-channel parallel flow condenser. The refrigeration circuit was equipped with a variable capacity compressor run by an electric motor controlled by a frequency converter.

Park et al. [67] developed a thermodynamic model for a refrigerant injected variable speed scroll compressor with using continuity energy conservation and real gas equation. In this model, energy balance at the low-pressure compressor, suction gas heating, motor efficiency, and volumetric efficiency were considered. Also, gas leaking was considered as a function of compressor frequency. Results showed deviations from the measured values about 10% at the 90% of the experimental data. According to the model, mass flow rate, suction gas heating, cooling capacity, and power consumption of the compressor were estimated and analyzed as a function of frequency. Furthermore, the effects of the injection on the performance of the compressor were discussed as a function of frequency, injection geometry, and injection conditions. Another modeling study was investigated by Aprea and Renno [68]. The main aim of this study is a thermodynamic model simulating the working of a vapor compression refrigeration system. The model could evaluate the system performance, while the compressor capacity is regulated with an inverter inserted into the compressor electric motor. The author compared the outputs of the model with the experimental results. The comparison of model and experimental results is realized by varying the supply of current frequency of the compressor in the range 30–50 Hz using the R407C. The model and experimental result comparison is completely acceptable in terms of condensation temperature, compression ratio, condensation power, and coefficient of performance. Also, an exergetic analysis represented to explain the performance of the plant components at variable speed operation.

In addition to this study, Shao et al. [69] analyzed modeling of variable speed compressor for air-conditioner and heat pump. For the real operation performance of inverter-driven compressor, a map-based method was used. Since the second-order function of condensation and evaporation temperature, the model was built at the basic frequency and map conditions. The model is validated by the actual operating conditions. The author compared the data provided by the compressor manufacturers, the average relative errors are less than 2, 3, and 4% for refrigerant mass flow rate, compressor power input, and coefficient of performance (COP), respectively, and the author found out that this model of variable speed compressor is suitable for the simulation of inverter air-conditioner and heat pump systems.

Kim and Kim [70] studied on an experimental study to define the effect of four artificial faults on the performance for a variable speed refrigeration system. For the evaluation of the performance, a conventional vapor compression test system was modified to test several artificial faults by observing the variation of cooling capacity. The four major faults were compressor fault, condenser fault, evaporator fault, and refrigerant leakage. Two different rule-based modules for constant and variable speed operations were organized for an easy diagnosis of the faults. As a result, COP degradation due to the fault in a variable speed system was severer than that in a constant speed system.

Cho et al. [71] measured the cooling performance of a variable speed CO_2 cycle and analyzed by varying the refrigerant charge amount, compressor frequency, EEV opening, and length of an internal heat exchanger (IHX). As a result the cooling COP decreased with the increase of compressor frequency at all normalized charges. The optimum EEV opening increased with compressor frequency. The optimal compressor discharge pressure of the modified CO_2 cycle with the IHX was reduced by 0.5 MPa. The IHX increased the cooling capacity and COP of the CO_2 cycle by 6.2–11.9% and 7.1–9.1%, respectively, at the tested compressor frequencies from 40 to 60 Hz.

In addition to these studies, the Ekren and Kucuka study [72] has been carried out by a fuzzy logic-controlled chiller system with variable speed compressor. In this study, not only variable capacity modulation has been studied, but also fuzzy logic control effect on chiller system has been investigated. Scroll compressor, designed to study as fixed-speed compressor, was operated as variable speed with a PWM inverter. Also, electronic expansion valve, fuzzy controlled, was used. In this system 33.4% COP increase was obtained according to on-/off-controlled system. This increase has been obtained because of the less temperature difference between condensing and evaporation temperature.

3. Electrical control research for capacity-modulated refrigeration systems

Any system, whose outputs are controlled by some inputs of the system, is called a control system. Electrical control techniques of the capacity-modulated refrigeration systems are very important, because of the quick response of the load changes. On/off control, proportional-integral-derivative (PID), stochastic control, adaptive control, nonlinear methods, and robust control are known as conventional control systems. On/off and PID controls are the most commonly used methods in the heating ventilating and air-conditioning system control. Recent developments in artificial intelligence-based control systems have brought into focus a possibility of replacing control system with fuzzy logic control (FLC) equivalent. Therefore, fuzzy logic control is needed in the investigation on capacity-controlled refrigeration system. A standard PID controller is based on mathematical modeling of the system being controlled, whereas a fuzzy logic controls relies on physical rules rather than mathematical equations. In addition, fuzzy logic control provides a formal methodology for representing, manipulating, and implementing a human's heuristic knowledge about how to control a system.

Comparison of fuzzy logic and conventional controllers for a refrigeration system was investigated by Cheung and Kamal [73]. Fuzzy control application is realized on various compressor types following two authors. Aprea et al. [74] investigated fuzzy logic-based control algorithm which could select the most suitable compressor speed according to function of the cold store room air temperature. They found that this algorithm provides 13% energy saving when the R407C refrigerant was used at fuzzy logic-controlled variable speed reciprocating compressor. Furthermore, regarding the inverter cost, the payback period was more acceptable than for the examined cold storage plant.

Aprea and Mastrullo [75] investigated a vapor compression system which is able to operate as a water chiller and as a heat pump. The main aim of this study is to evaluate energy-saving potential of a scroll compressor at varying speed instead of classical thermostatic (on/off) control. The compressor speed was continuously controlled via fuzzy logic algorithm. For different working conditions, a significant energy saving on average equal to about 20% was obtained adopting a scroll compressor speed control algorithm, based on the fuzzy logic, in comparison with the classical thermostatic control.

In a different study by Aprea et al. [76], energy consumption of an electronic valve and a thermostatic expansion valve were compared in a cold store. The main aim of the study was to verify the best type of expansion valve for the energy point of view. The results showed that with a fuzzy algorithm, the thermostatic expansion valve allows an energy saving of about 8% in comparison with the electronic valve.

Heating, ventilating, and air-conditioning (HVAC) control application is also studied in control researches, broadly. Rahmati et al. [77] presented a new approach to control heating, ventilating, and air-conditioning (HVAC) system. The proposed method was a hybrid of fuzzy logic and PID controller. Fuzzy logic control showed better control performance than PID controller. According to Wang et al. [78], the controlled object in HVAC system has large inertia, pure lag, and nonlinear characteristic. Combined with the fuzzy control and general PID control, the temperature and humidity of the room were controlled in HVAC system of a TV building. The temperature of the studio was controlled through PID control, fuzzy control, and fuzzy-PID control. It was found that hybrid fuzzy-PID control has better adaptability and stability, less overshoot, faster response, and higher precision than PID control and fuzzy control. Navale [79] conducted experiments on two real HVAC systems to compare the performance of fuzz logic control and PID control. Results of this study showed that fuzzy control system required 0–185% more rise time, had 9–68% less overshoot, and required 11–45% less settling time as compared to the conventional PID-controlled system.

In a different study from the others, Li et al. [80] investigated a PID and a fuzzy logic control study for automobile air-conditioning system. In the study, improvement of the refrigerant flow control method by using an electronic expansion valve (EEV) was described. Also, the flow rate characteristic of the EEV for automobile air-conditioning was presented. A microcontroller was used to receive input signal and generate output signal to control the opening amount of the EEV. They employed a fuzzy self-tuning proportional-integral-derivative (PID) control method. Experimental results showed that the new control method can feed adequate refrigerant flow into the evaporator in various operations. Also, evaporator discharge air temperature dropped by approximately 3°C as compared with the conventional PID control system.

4. Conclusion

In this paper, the literature review of capacity control methods is completed. The application of capacity control methods to refrigeration systems offers the potential for substantial energy saving or energy efficiency. Also, it is known that the overall energy consumption of a refrigeration, air-conditioning, or heat pump during its service life is a considerable cost factor and frequently is a multiple of the initial investment. Consequently, with a view to indirect environmental impact (CO_2 emission due to power generation), optimum capacity control should be aimed for, that is, closely matched to demand. According to previous researches, variable speed capacity control is the most common and efficient methods in the capacity control studies. In addition to this, both of variable speed and digital scroll modulation present close modulation result. Also, it is seen that artificial intelligence control techniques show superiority toward conventional control methods on refrigeration system.

Author details

Orhan Ekren

Address all correspondence to: orhanekren@gmail.com

Solar Energy Institute, Ege University, İzmir, Turkey

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