Techno-Economic and Environmental Assesment of Compressor Retrofitting Procedure

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Abstract: In this study, retrofitting of a fixed speed refrigeration system to a variable speed refrigeration system is investigated. Economical and technical benefits of the retrofitting procedure are also studied. Refrigeration systems are usually designed to overcome maximum load conditions. However, they work under partial load in most of their life cycle. Hence, in this study a variable speed compressor that equalizes the cooling load to the demand that assures significant energy saving is considered. As a result of this study, the retrofitted variable speed compressor performed 17% decreased energy consumption versus the thermostatic controlled fixed speed system. Also, the retrofitting procedure provided considerable payback time. From the result, 10750 kilograms less carbon emission per year as an environmental benefit within retrofitting procedure is obtained.

Keywords: Energy saving, carbon emission, greenhouse gas, variable speed compressor, retrofitting compressor.

1. INTRODUCTION

Energy conservation and reduction of global warming effect are the most important issues in the worldwide. Hence, to meet energy demand with a minimum cost and to assure sustainable environment became the most important problem. Global CO_2 emission because of energy usage was 34% higher in 2006 than in 1990. Therefore CO_2 emission produced by any system directly or indirectly must be under control. Trends in CO_2 emissions vary significantly between countries as seen in Figure **1**. Developing countries with high economic growth have doubled their CO_2 emissions, while Europe has nearly stabilized its emission because of climate policies (WEC, 2007).

At least by 2050, the world will need to double today's level of energy supply to meet increased demand (WEC, 2008). The inefficient use of electricity in refrigeration systems is regarded as an indirect contributor to the emission of greenhouse gases to the atmosphere. These emissions can be decreased by more efficient energy conversion in all systems. Since the refrigeration systems' energy consumption is about 40% of overall energy consumption, these systems are under study. Generally, a refrigeration system is being selected to overcome the worst conditions. But it delivers high cooling capacity and needs to be cycled on/off when normal conditions occur. However, refrigeration systems are operated at partial loads most of their lifecycles. For example, chillers run at part-loadin 99% of their life cycle (ARI, 2003). Therefore, toincrease the refrigeration systems' partial load efficiency is mandatory. Cooling capacity modulation equalizes system capacity to load and, improves overall system efficiency at partial load. Widely known capacity modulation methods are: on/off control, digital scroll compressor, cylinder unloading, hot gas bypass, slide valve, multiple compressor operation and variable speed compressor (Tassou, 1983; Janssen, 1984; Zubair, 1989; BIR, 2006). In this study, the variable speed capacity modulation method is investigated. The main aim of this study is to analyze the environmental and technical benefits of the retrofitted variable speed compressor and retrofitting procedure. It is obvious that renewing any fixed speed refrigeration system that has not completed its life cycle is an expensive way. On the other hand, energy consumption of this type refrigeration system should be decreased as mentioned before. Besides, energy efficiency regulations force this enhancement. Therefore, in this paper retrofitting procedure of a fixed speed refrigeration system to a variable speed system is studied. Three cases are considered and their results are compared.

2. EXPERIMENTAL

The experimental chiller system has a vapor compression refrigeration cycle working with the refrigerant R134a. The system consists of a scroll compressor, a shell-tube liquid type evaporator, an air-cooled condenser inside the thermally insulated air channel. Besides this, an electrical heater, a fan, and a nozzle are mounted in the insulated air channel. To simulate the external conditions, air flow rate and temperature can be changed by a fan and an electrical heater, respectively. In addition to the electronic expansion valve (EEV), a thermostatic expansion valve (TXV) is mounted in order to realize on/off controlled fixed speed compressor case. The system also has a

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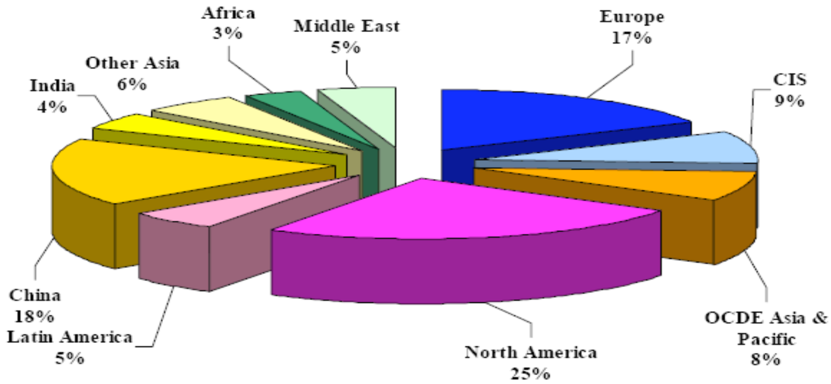

Figure 1: Distribution of world CO_2 emissions from energy use.

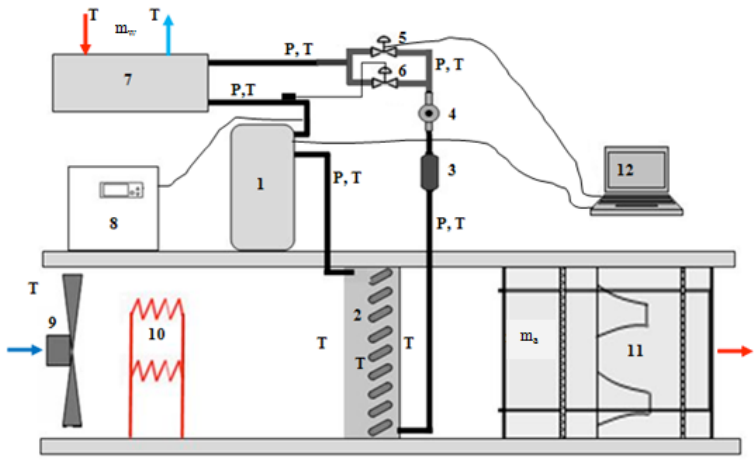

Figure 2: Schematic illustration of the experimental plant.

filter drier, a solenoid valve, as well as a water tank. During the experiments, to obtain a constant cooling load in the evaporator, electrical heaters are used in the water tank. It is necessary to measure the temperature, pressure, and mass flow rate for the thermodynamic analysis. The temperatures are measured by the 'T'-type thermocouples over the cooling cycle. The gauge pressures are measured by the ratiometric type pressure transducers at the inlet and outlet of the evaporator, condenser, and compressor. Also the power consumption of the compressor is measured by a wattmeter. Electricity consumption of the PWM inverter is not taken into account to measure the compressor's electricity consumption. A control and a data acquisition unit are installed to send a control signal to the compressor and EEV. Control signal for the EEV is sent through the computer parallel port without using any microcontroller. The experimental setup allows us to vary the compressor electric motor frequency and voltage by means of an inverter. At the out point of the inverter, the voltage is adjustable in frequency and magnitude with constant *V*/*f* ratio. This method allows considerable capacity modulation for the refrigeration system. Schematic illustration of the experimental plant is given in Figure **2**.

In Figure **2**, the components of the plant are given by: 1 - compressor, 2 - condenser, 3 - dryer, 4 – sight glass, 5 - EEV, 6 - TXV, 7 - evaporator, 8 - control panel, 9 - fan, 10 - electrical heater, 11 - nozzle, and 12 - compressor and EEV control unit. In Figure **2**, the measurement point of the temperature, pressure, and flow rate on the cooling cycle are shown by the notations *T*, *P*, and *m*, respectively. Air and water inlet, and outlet are illustrated by arrows. The specifications of the equipment are given in Table **1** (Ekren and Küçüka, 2009).

3. TECHNO-ECONOMIC EVALUATION OF THE RETROFITTING PROCEDURE

In this study, a scroll compressor is used to ensure a variable speed operation. This compressor is produced to be operated at fixed speed, e.g. 50 Hz. During the retrofitting procedure a PWM inverter is added to operate the compressor as variable speed. The retrofitting compressor`s speed range is changed between 30 - 60 Hz. In contrast, an original variable

Table 1: Specifications of the Experimental Plant (Ekren and Küçüka, 2009)

Equipments	Specifications
Compressor	Type: Copeland ZR34K3-PFJ, vertical scroll (R134a refrigerant) Capacity: 2.8 Hp, 380 V, 50 Hz
Condenser	Type: Air cooled
Evaporator	Type: Shell-tube liquid
Expansion valve	Type: Electronic Port size: 1.8 mm Operating range: 0–480 pulse Rated voltage: DC 12 V Control method: Stepper motor controlled
Pressure Transducer	Type: Carel SPKT, Ratiometric Range: low pressure (between -1 and 9 bar), high pressure (between 0 and 45 bar) absolute Error: ±%1.2
Thermocouple	Type: "T" Range: -200 and 350 ^{o}C Error: ±%1.5
Wattmeter	Type: Bs157 Range: 220/600 V , 50/60 Hz Error: ±%1.5
Data Acquisition and Control System	Agilent-34970 data logger and 34907 control card Stepper control circuit and PC parallel port
Inverter	Type: PWM Capacity: 2.2 kW Frequency Range: 0-100 Hz

speed compressor has speed range between 20 to 80 Hz. A fuzzy logic control algorithm is developed to control the compressor and EEV. In this section, techno-economic analysis is completed with respect to the energy saving and COP increase. Three cases are compared: first, the retrofitted variable speed compressor operation is considered, second, an original variable speed compressor and last a fixed speed operation are considered. A detailed comparison of each case's cost is provided in Table **2**.

For the calculation of energy consumption, it is assumed that the chiller system operates 20 hours a day, 30 days in a month and 12 months in a year. The unit cost of the electricity is considered as 0.08 € kWh^{-1}. Under these conditions the comparison is completed versus fixed speed system.

According to the experiments the retrofitted variable speed compressor has 1.157 kWh average electricity consumption. The original variable speed compressor has 1.057 kWh average electricity consumption and, the fixed speed compressor`s average electricity consumption is 1.357 kWh.

4. CALCULATION CO_2 EMISSION PRODUCED BY A REFRIGERATION SYSTEM

In many countries, reducing CO_2 emission is obligated by regulations. These regulations are used to stabilize global warming by reducing greenhouse gases. Monitoring, collecting data and performing detailed reporting of CO_2 sources are necessary to calculate the CO_2 emissions. The refrigeration system's CO_2 emission production is measured by electricity usage as "kilowatt hours". This can be monthly or total

Table 2: Cost of the Equipments

Equipments	Specifications	Cost (€)
PWM Inverter	2.2 kW, 3 ph inverter	275
EEV	Stepper motor operated	250
Original Variable Speed Compressor	2.1 kW, Scroll type (20-120 Hz)	900

Table 3: Economical Aspects

Case	Average Electricity Consumption (kWh)	Yearly Electricity Consumption (kWh)	Yearly Electricity Cost (€)	Savings Respect to Fixed Speed System (€)	Payback Time (year)
Case-1: Adding Inverter and EEV (525 €)	1.157	(7200x1.157) 8330.4	(0.08x8330.4) 666.43	115.2	4.55
Case-2: Original Variable Speed Compressor and EEV (1150 €)	1.057	(7200x1.057) 7610.4	(0.08x7610.4) 608.83	172.8	6.65
Case-3: Fixed Speed Compressor Case	1.357	(7200x1.357) 9770.4	(0.08x9770.4) 781.63	-	-

electricity usage. One kWh electricity usage causes 7.5 kilograms of CO_2 emission in the refrigeration system. For instance, to calculate the CO_2 emission, monthly electricity usage (in kWh) needs to be multiplied by 7.5. Similarly, one cubic meter natural-gas usage creates 1.94 kilograms of CO_2 emission and one liter of gas usage by driving vehicle creates 2.32 kilograms of CO_2 emission (EPA, 2009). The detail of the comparison is shown in Table **3**.

4.1. Reducing CO_2 Emission by Retrofitting Procedure

Most of the studies in the literature related with variable speed refrigeration systems suffer from the agreeable control of the compressor and EEV. In our study, the control algorithm provides reasonable results (Ekren et. al., 2010). One can clearly observe from the graphical results that the retrofitted variable speed compressor exhibits more reasonable control for the water temperature control than the on/off controlled fixed speed compressor. In addition, the power consumption of the retrofitted compressor is lower than the on/off controlled fixed speed compressor. The power consumption of the compressor is illustrated in the Figure **3**. From the Figure it is understood that 1.157 kWh electricity consumptions on average for the retrofitted variable speed compressor is obtained. On the other hand it is observed that the electricity consumption before the retrofitting procedure for the on/off controlled fixed speed compressor is 1.357 kWh. The reduction of electricity consumption is crucial for the CO_2 emission control. It is observed 8.67 (7.5x1.157) kilograms CO_2 emission per hour after the retrofitting procedure. It was 10.11 (7.5x1.357) kilograms per hour before the retrofitting.

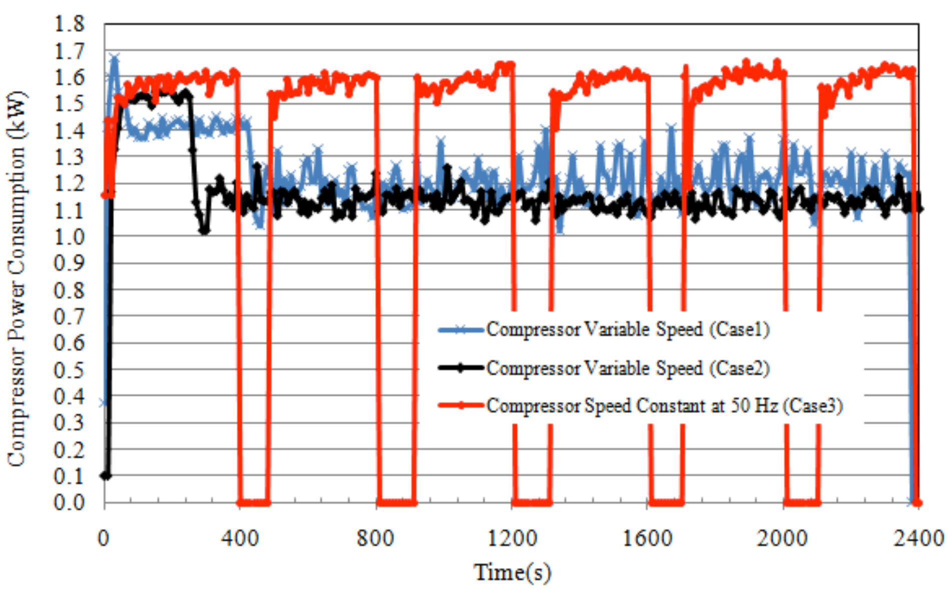

Figure 3: Compressor power consumptions.

Consequently, it is observed 1440 kWh yearly energy saving with the retrofitting a fixed speed compressor to a variable speed in a chiller for 7200 hours of operation. In another word, this means that 10750 kilograms of CO_2 emission reduction per year *via* retrofitting of the compressor.

5. RESULTS AND DISCUSSIONS

In this study, an energy saving potential of a retrofitted scroll compressor is compared versus an on/off controlled fixed speed compressor. During the experiment -2400 s periods- the produced cool for the fixed speed compressor is 5935.3 kJ and the compressor energy consumption is 3256.8 kJ. Under these conditions, COP value is 1.822. For the retrofitted variable speed compressor operation, 5935.3 kJ cool is produced and 2776.8 kJ energy is consumed by the compressor. COP value is 2.13 under these conditions. A considerable performance improvement -17% - is obtained by the retrofitted variable speed compressor and EEV compared to the on/off controlled fixed speed compressor. As a result, the retrofitted system by adding an inverter and EEV shows shorter payback time than the original variable speed compressor. Furthermore, 10750 kilograms CO_2 emission reduction is obtained per year *via* retrofitting of the compressor.

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