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ABSTRACT

Rising cooling needs for the residential and commercial air conditioning sectors and the requirement of higher SEER values increased the focus on energy-efficient part load performance. Although several studies exist on the topic of capacity modulation, there is no comprehensive study that compares different modulation strategies in the same experimental facility. In a first step, this paper aims to experimentally compare two different capacity controls for scroll compressors (single speed vs two-stage compressor) using the same R410A water ethylene glycol (WEG) chiller having a nominal cooling capacity of 8kW. The tests were conducted according to AHRI Standard 551/591 (2018). The Integrated Part Load Value (IPLV.SI) was used to fairly compare all these capacity modulation strategies. Based on the experimental results, the difference in the order of 8% in IPLV.SI is found. While both compressors showed comparable capacities and COPs at the higher modulation conditions, two stage compressor has better COP at the lower condition because of its ability to operate at a lower stage and better meet the required load.

1. INTRODUCTION

Almost all HVAC&R systems need to be designed to handle cooling loads below the target or design condition. These load variations are often caused by ambient weather variations, different levels of product loading, or the fact that systems are overdesigned to achieve quick pull-down. The range of load variations can be very substantial, in some cases even down to 30% or less of the design capacity. Different capacity control strategies employ different methods so that they can be implemented into the compressor or outside the compressor, in which case the system needs to provide adequate provisions. The modulation target is the same across the different techniques employed: the (average) refrigerant flow rate across the evaporator is reduced to adjust for the different levels of cooling capacity needed. There are many different methods of how to achieve this goal.

The main shortcoming of any literature-based comparison to the best of our knowledge is the fact that different data sets were obtained with different systems using different refrigerants, evaporation and condensation temperatures, secondary flow rates, and different levels of system controls. It is therefore nearly impossible to derive meaningful comparisons between the different studies when it comes to efficiency.

As a first step, this paper aims to experimentally compare two capacity modulation strategies, a single speed scroll compressor and a two stage scroll compressor using the same R410A WEG chiller system. These compressors have the comparable nominal cooling capacity. The tests are conducted according to AHRI Standard 551/591 (2018) and the comparison is done using a single figure of merit called IPLV.SI (Integrated Part Load Value).

2. MODULATION STRATEGIES BEING CONSIDERED

The following are the different compressor modulation strategies being considered as part of this study. As a first step, this paper compares a single speed and two stage compressor. All the compressors are scroll and have similar capacity and belong to the same generation.

2.1 Single speed compressor

A single speed compressor modulates capacity by cycling i.e. turning on and off. The on/off capacity control is the simplest method of adjusting the predetermined temperature (setpoint) using a thermostat. After the temperature reaches the setpoint, the 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, this rise turns the compressor on (Ekren, 2017).

2.2 Two stage compressor

This is a commercially available two stage compressor. It is different from conventional two stage compressors that use a low-pressure stage and a high-pressure stage. Instead, it has two internal bypass ports which enable the system to run at 67%-part load capacity. If the compressor is operated at the same condenser and evaporator water temperature, then the capacity at the 67% stage is approximately 67% of the capacity at the 100% stage. This compressor can be operated either at a high stage (100% capacity) or a low stage (67% capacity). The capacity is reduced by bypassing a portion of the gas in the scroll back to suction. These bypass ports are opened or closed using a solenoid valve present in the scroll chamber (Wang *et al.*, 2012).

2.3 Variable speed compressor

This compressor modulates its capacity by varying the speed of the motor (Qureshi and Tassou, 1996). The focus will be on the inverter driver variable speed compressor with a brushless DC motor. The selected compressor can be operated between 20 Hz and 100 Hz.

2.4 Digital scroll compressor

In this commercially available compressor, the modulation is achieved through rapid engagement/disengagement of the upper scroll (using a piston and solenoid valve). The scrolls are separated in a periodic cycle to obtain a time-averaged capacity based on the ratio of loading and unloading times. This provides a modulation range from 10% to 100% (Wu and Wu, 2004).

2.5 Tandem compressors

In this configuration multiple compressors operate in parallel. The modulation is achieved by turning a different combination of compressors on and off (Cecchinato, 2010). This study will cover a tandem combination of two compressors. The study will include combinations of a single speed compressor with a variable speed, digital scroll, two stage, and another single speed compressor.

3. DETAILS OF THE EXPERIMENTAL SETUP

Figure 1 shows the schematic of R410A Water Ethylene Glycol (WEG) chiller. A mixture of 20 % water and ethylene glycol is used as the secondary fluid. Two closed WEG loops are connected to the evaporator and condenser. Variable speed pumps and electric heaters are used to control the WEG flow rate and the inlet temperature of the condenser and the outlet temperature of the evaporator. An additional heat exchanger with chilled water flowing through is included in the condenser WEG loop to reject the heat from the condenser WEG loop. All the heat exchangers used in the facility are brazed plate heat exchangers. A 0.9 L receiver is connected between the condenser and the subcooler. Superheat is controlled by an Electronic Expansion Valve (EEV) while the subcooling is a function of the charge. The geometric dimensions of the evaporator, condenser, and subcooler can be found in Table 1. Both the compressors used are scroll compressors with a nominal speed of 1800 min^{-1}.

Type-T thermocouples, absolute and differential pressure transducers, and Coriolis-type mass flow meters are used to obtain the refrigerant side measurements while type-T thermocouples, differential pressure transducers, and Coriolis-type mass flow meters are used to obtain WEG measurements. Data is collected at steady-state conditions at 5s intervals for 20 consecutive minutes, and the data is averaged over the collection period. REFPROP 10.0 was used to calculate the WEG and R410A properties (Lemmon *et al.*, 2012).

The uncertainties of the calculated properties associated with the instrument uncertainties of measured properties are calculated by uncertainty propagation as shown in Equation (1):

$$U_Y = \sqrt{\sum_i (\partial Y/\partial X_i)^2 U_{X_i}^2} \tag{1}$$

where U_Y is the uncertainty of calculated property and U_{X_i} is the uncertainty of measured property. The uncertainty of the other sensors used in the experimental facility is presented in Table 2. This uncertainty estimation does not include the uncertainty in thermophysical properties. However, the uncertainty in enthalpy difference can be approximated as the uncertainty in specific heat which is around ±0.5% (Lemmon *et al.*, 2012).

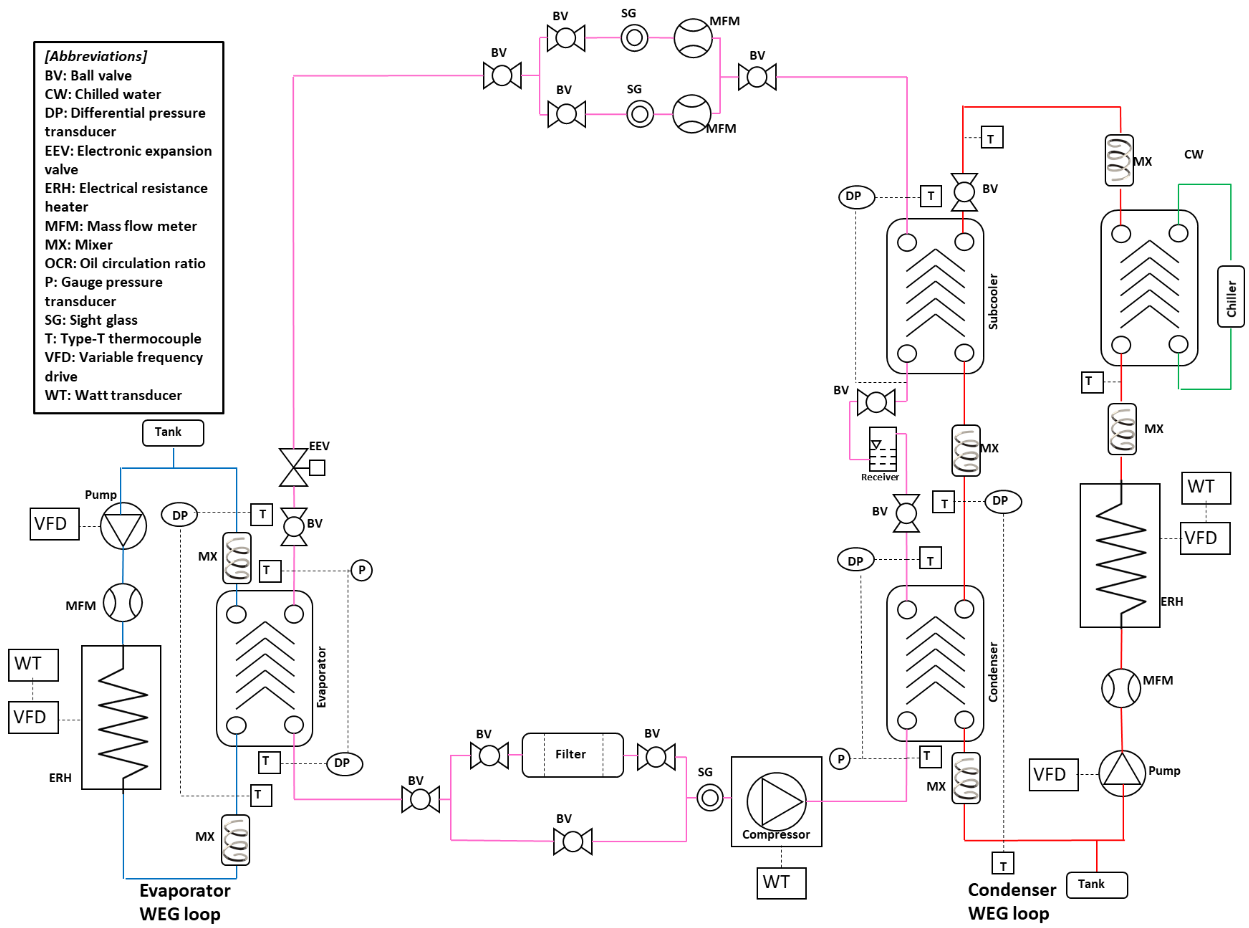

Figure 1: Schematic of the R410A experimental facility

Table 1: Dimensions of the brazed plate heat exchangers

Heat exchanger	Length (mm)	Width (mm)	Number of plates
Evaporator	311	111	28
Condenser	311	111	14
Subcooler	207	77	14

Table 2: Summary of measured and calculated property uncertainties

Instrument	Thermocouple (°C)	Pressure transducer (kPa)	Mass flow meter (g/s)	Wattmeter (kW)	Capacity (kW)	COP (-)
Uncertainty	±0.1	±0.2%	±0.2%	±0.5%	±1.5%	±1.6%

Capacity is calculated on the refrigerant side and WEG side. For the WEG side, mass flow rate, temperature, and specific heat are used to calculate capacity as shown in Equation (2). For the refrigerant side, temperature and pressure are used to calculate the enthalpy which is then used with the mass flow rate to calculate the capacity as shown in Equation (3). The capacity reported is the average of the refrigerant side and WEG side capacity given by Equation (4). The difference between the two capacities is indicated by the error given by Equation (5). This error is always less than 3% for the part load rating tests. Power consumed by the compressor is measured using a Wattmeter. The ratio of the average capacity and power consumed by the compressor is used to calculate the COP_{test} as shown in Equation (6).

$$\dot{Q}_{ev,WEG} = \dot{m}_{WEG} C_p \Delta T \tag{2}$$

$$\dot{Q}_{ev,ref} = \dot{m}_{ref} \Delta h \tag{3}$$

$$\dot{Q}_{ev,avg} = \frac{(\dot{Q}_{ev,WEG} + \dot{Q}_{ev,ref})}{2} \tag{4}$$

$$\varepsilon_{Qev} = \frac{(\dot{Q}_{ev,avg} - \dot{Q}_{ev,WEG}) \cdot 100}{\dot{Q}_{ev,avg}} \tag{5}$$

$$COP_{test} = {}^{\dot{Q}_{ev,avg}}\!\big/_{\dot{W}_{cp}} \tag{6}$$

4. AHRI 551/591 (2018) STANDARD

AHRI 551/591 is used for the determination of the part-load performance of water chillers. The standard defines a single number part-load efficiency figure of merit called Integrated Part Load Value (IPLV.SI) calculated at part load rating conditions. These part load rating conditions are shown below in Table 3. IPLV.SI is the weighted average of the COP_R measured at these standard rating conditions as shown in Equation (7). These factors in Equation (7) are based on the weighted average of the most common building types and operations using average weather in 29 U.S cities.

$$IPLV.SI = 0.01 \cdot A + 0.42 \cdot B + 0.45 \cdot C + 0.12 \cdot D \tag{7}$$

$$A = COP_R \; at \; 100\%$$
$$B = COP_R \; at \; 75\%$$
$$C = COP_R \; at \; 50\%$$
$$D = COP_R \; at \; 25\%$$

If a compressor cannot be unloaded to 25%, 50%, or 75% load point, then the compressor is run at the minimum step of unloading at the condenser entering water shown in Table 3 for 25%, 50%, or 75% capacity points as required. Once the COP_{test} is calculated at these conditions using Equation (6), it is degraded to COP_R using the Equation (8), (9), (10), and (11).

$$COP_R = {}^{COP_{test}}\!\big/_{C_D} \tag{8}$$

$$C_D = (-0.13 \cdot LF) + 1.13 \tag{9}$$

$$LF = \frac{(\%Load)(Q_{ev\ 100\%})}{(Q_{ev\ min\%Load})} \tag{10}$$

$$\%Load = {(Part\ load\ net\ capacity)}\Big/{(Full\ load\ rated\ net\ capacity)} \tag{11}$$

Table 3: AHRI 551/591 part load conditions for IPLV.SI

Condition	Part load ratio (%)	Condenser Inlet/Outlet (°C)	Evaporator Inlet/Outlet (°C)
A	100	30/35	12/7
B	75	24.5/*	*/7
C	50	19/*	*/7
D	25	19/*	*/7

Table 3 shows the part load conditions. As seen in the table, condenser inlet, outlet, and evaporator inlet, outlet are mentioned for A condition while for the B, C, and D conditions, only the condenser inlet and evaporator outlet temperature are mentioned. Standard required that the condenser and evaporator WEG flow rate used for the A condition be used for the B, C, and D conditions.

5. RESULTS

Before testing the compressor at the part load rating conditions, charge optimization was done at the A condition i.e. condenser WEG inlet temperature of 30°C for both the compressors to determine the optimum charge for the compressor. After that, the compressors are tested at the part load rating conditions at their respective optimum charge. The next section shows the charge optimization of a single speed compressor.

5.1 Charge optimization of a single speed compressor

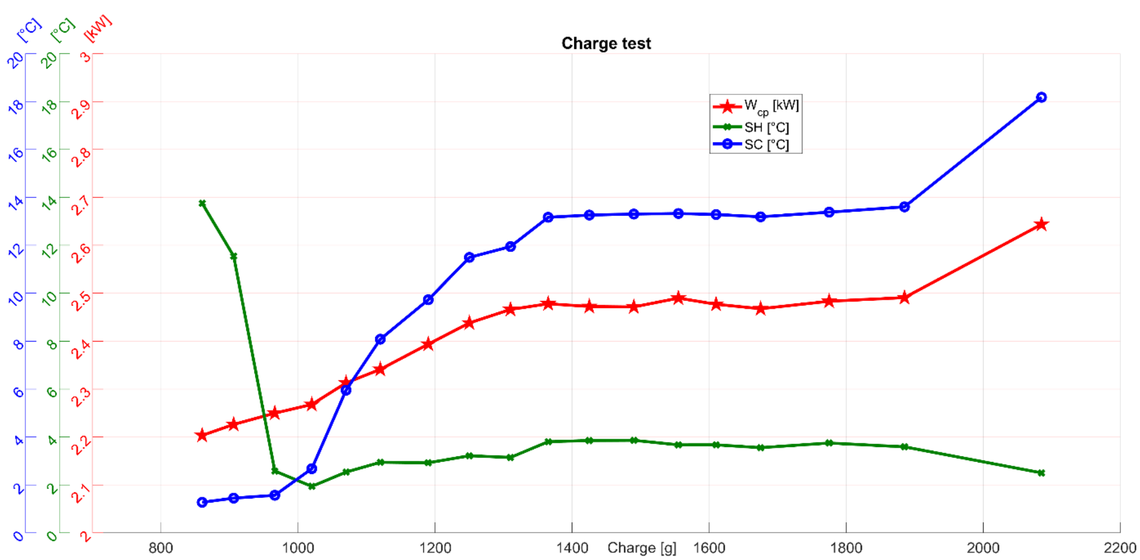

Figure 2: Variation of W_{cp}, superheat and subcooling with charge

Figure 2 shows the variation of the compressor work, superheat, and subcooling with the charge. As the charge increases, subcooling increases until it reaches a plateau. Superheat remains the same after the first few points because the EEV maintains the same superheat. The high superheat at the initial charge is because of the undercharged system. Figure 3 shows the variation of COP, average capacity, and the compressor discharge pressure with the charge. There is a range of charge from 1300 g to 1800 g where the curves remain almost constant. This range exists because of the receiver present after the condenser. As the charge increases in this range, the receiver gets filled and the amount of charge present in the remaining system remains almost constant. If the charge is increased beyond this charge, the receiver can no longer hold the charge and liquid starts backing up in the condenser. This is seen by an increase in the compressor discharge pressure and increase in the subcooling. A charge of 1500 g is selected as the optimum charge.

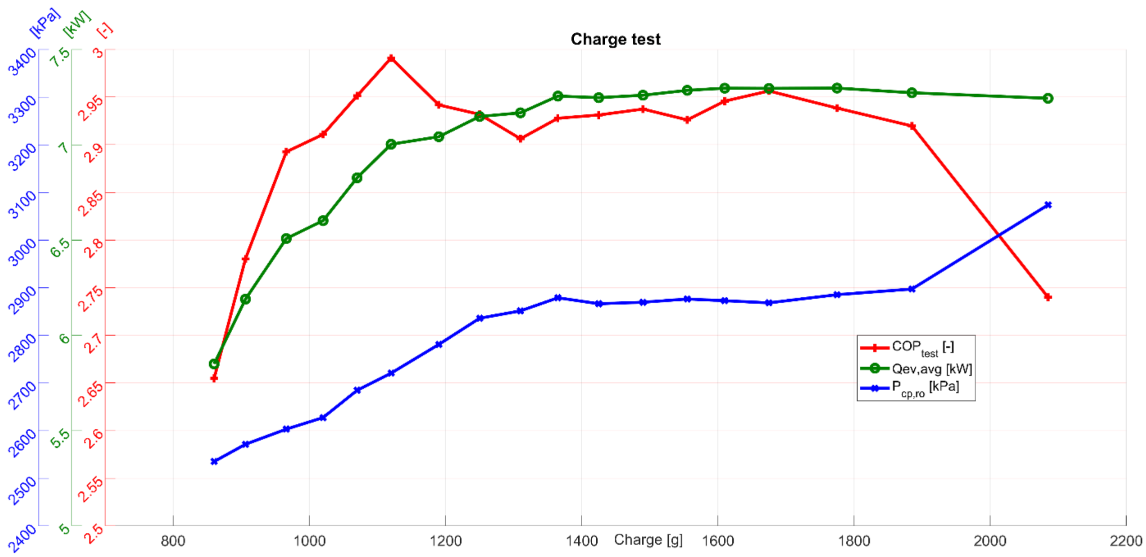

Figure 3: Variation of COP_{test}, $Q_{ev,avg}$, and $P_{cp,ro}$ with charge

5.2 Single speed compressor part load performance

As explained before, as single speed compressor does not have any modulation, it can operate only at 60 Hz. The variation of the capacity with part load rating conditions is shown in Figure 4. The load is a linear function of the part load rating conditions.

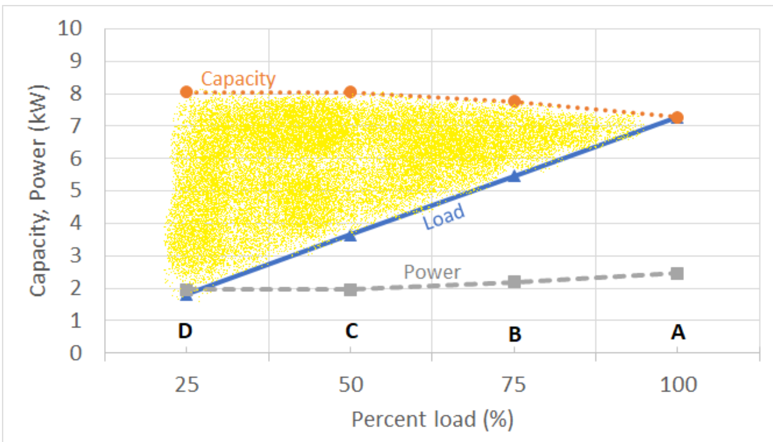

Figure 4: Variation of capacity, power with percent load for single speed compressor

As seen in Figure 4, as the percent load changes from 100% to 25%, the standard requires a reduced condenser WEG inlet temperature, this reduces the condensing temperature which in turn causes the capacity to increase. The shaded region between the capacity curve and the load curve is an indication of how much the obtained capacity differs from the required load and is a representation of the cycling losses. The capacity remains constant for the C and D conditions because the condenser WEG entering temperature is maintained the same as required by Table 3, only the percent load changes. Since a single speed compressor only operates at one stage, and thus the performance of the compressor at these percent loads is the same. As expected, the compressor power reduces as the percent load reduces because of reduced condensing temperature and compressor discharge pressure.

5.3 Two stage compressor part load performance

A two stage compressor can be operated at either high stage (100%) or low stage (67%). The performance of this compressor at different part load conditions is shown in Figure 5.

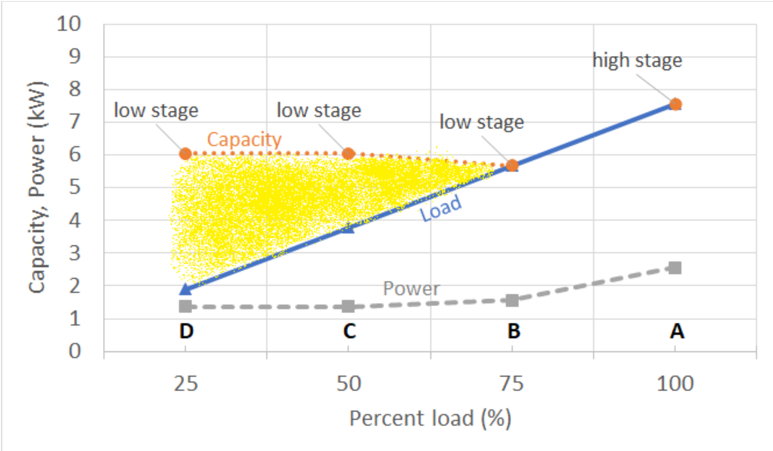

Figure 5: Variation of capacity, power with percent load for two stage compressor

For the A condition, the compressor is operated at a high stage. For the B, C, and D conditions, as the required load reduces, the compressor is operated at the low stage. The capacity is not a continuous line between A and B conditions because this compressor does not provide a continuous modulation, it provides a step modulation. At the B condition when the compressor is operated at a low stage, it provides 75% capacity which matches the required load. However, at the C and D conditions, the low stage cannot match the capacity and it behaves similarly to a single speed compressor and hence there will be cycling losses. The shaded region is a representation of the cycling losses. By comparing Figures 4 and 5, you can see that the shaded region i.e. cycling losses are higher in a single speed compressor compared to a two stage compressor.

5.4 Comparison between single speed and two stage compressor

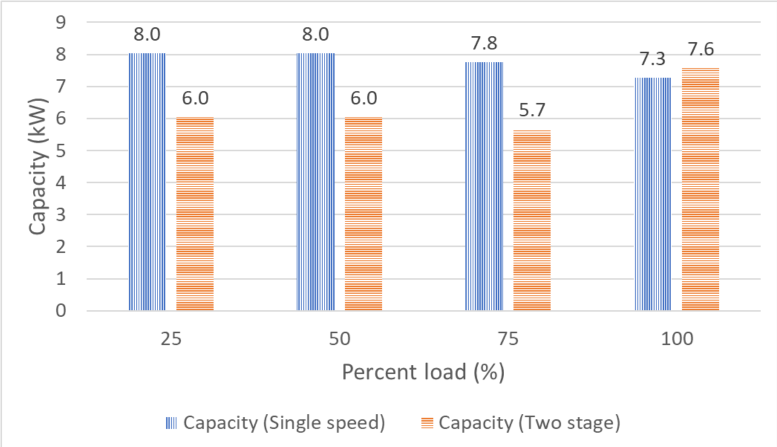

Figure 6: Comparison of capacity between single speed and two stage compressor

Figure 6 compares the capacities between a single speed and two stage compressor. At the 100% load, both the compressors have a similar capacity which indicates that both the compressors are comparable. However, for the remaining conditions, the single speed compressor has higher capacities than a two stage compressor because the two stage compressor can operate at a low stage.

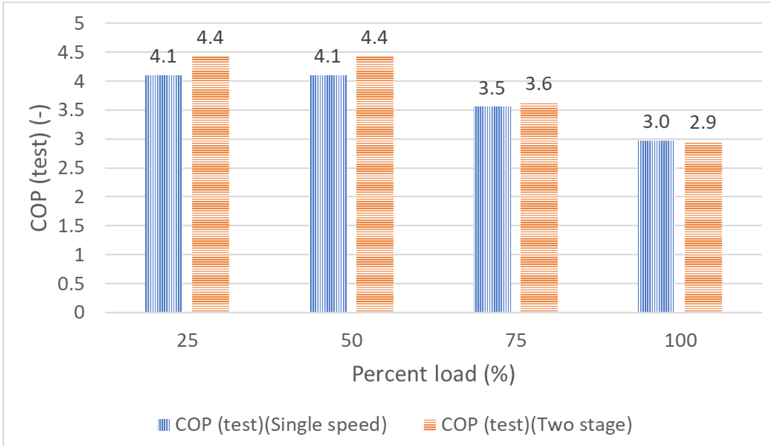

Figure 7: Comparison of COP_{test} between single speed and two stage compressor

Figure 7 shows the COP_{test} given by Equation (6). Both the compressors have similar capacity and power consumption at the 100% load, so it is not surprising that the COP_{test} are around the same. It is interesting to note that at the 75% load, though the two stage compressor is operating at the low stage and the single speed compressor is operating at its highest (only) stage, the COP_{test} are still comparable. However, the COP_{test} for the two stage is significantly higher at the lower percent loads because of reduced capacity and reduced compressor power. The COP_{test} for each compressor remains the same for the 50% and 25% load because the part load operating conditions are the same for these points.

Figure 8 shows the COP_R given by Equation (8). Except for the 100% load when both the compressors have similar performance, the two stage compressor has a higher COP_R than a single speed compressor. This is because of its ability to operate at lower stage. This trend can also be graphically explained by the cycling losses represented in Figures 4 and 5. Though the COP_{test} is the same for each compressor at the 25% and 50% load, COP_R at the 25% load is lower than 50% load because higher cycling losses reduce the COP_{test} by greater value as shown in Equation (9).

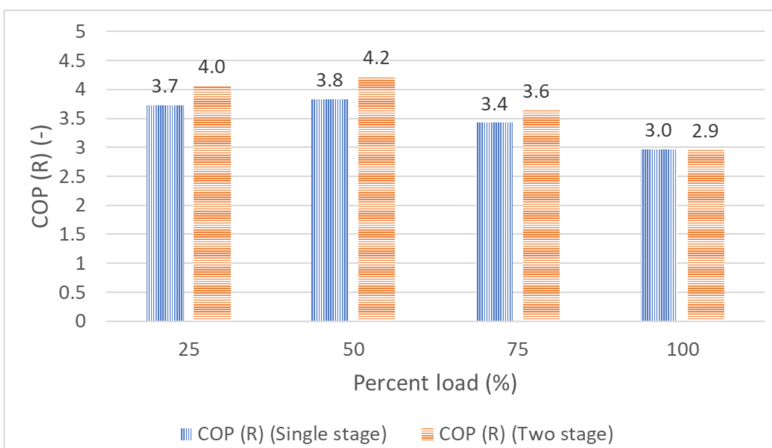

Figure 8: Comparison of COP_R between single speed and two stage compressor

IPLV.SI is calculated using the COP_R from Figure 8 and Equation (7). A single speed compressor has an IPLV.SI of 3.6 while the two stage compressor has an IPLV.SI of 3.9. This 7% difference can be explained by the higher COP_R of the two stage compressor at 50% and 75% load which have the highest weighting factors in Equation (7). A two stage compressor does not have any degradation coefficient at the 75% load and though it does incur some cycling losses at the 50% load, it is still operating at the low stage and these losses are lower than that incurred by the single speed compressor.

6. CONCLUSIONS

This study experimentally compared a single speed and a two stage compressor in the same R410A WEG chiller. Both the compressors have similar capacity and they belong to the same generation. Charge optimization was done to determine the optimum charge for both the compressor and AHRI 551/591 was used to determine the IPLV.SI for both the compressors at their respective optimum charge. Both compressors showed comparable capacities and COP_{test} at the higher modulation conditions. However, two stage compressor has a higher COP_R at the lower condition because of its ability to operate at a lower stage and better meet the required load, this reduces the C_D. Single speed compressor has an IPLV.SI of 3.6 while the two stage compressor has an IPLV.SI of 3.9.

NOMENCLATURE

C_d	degradation coefficient [-]	m	mass flow rate [kg/s]
COP	coefficient of performance [-]	Q	heat transfer rate [kW]
C_p	specific heat [kJ/kg-K]	SC	subcooling [°C]
ε	error [-]	SH	superheat [°C]
IPLV.SI	integrated part load value [-]	T	temperature [°C]
h	enthalpy [kJ/kg]	W	power [kW]
LF	load factor [-]	WEG	water ethylene glycol

Subscript

avg	average
cp	compressor
ev	evaporator
ref	refrigerant
ro	refrigerant, outlet
weg	water ethylene glycol mixture

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