Review on mathematical model developed for a valved linear compressor and its parametric analysis

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Abstract

L.G. Electronics revolutionized the field of household refrigeration by introducing an energy efficient option in the form of linear compressor. It consists of an oscillating motor coupled rigidly to a piston. This paper exhibits the developed mathematical model which includes the dynamic equation of a linear compressor consisting of inertia, motor force and damping. It also solves the electrical equation to calculate the current flowing through the motor circuit. To estimate the cylinder instantaneous temperature and pressure the program is interfaced with REFPROP.

For the given compressor geometry, the net cooling capacity, compressor input power and COP are determined by the model. The validation of this mathematical model is done with the experimental results reported by Lee et al.()

Various parameters like input voltage, refrigerant and superheating temperature of the refrigerant are varied in the parametric analysis. Results produced by this model are exhibited.

Keywords: Linear compressor, mathematical model,

Nomenclature

A	area (m^2)
B	magnetic flux (Wbm^{-2})
BDC	Bottom dead centre
C	Damping coefficient of piston
COP	Coefficient of Performance
D	Diameter (m)
F	Motor force (N)
f_n	Frequency (Hz)
h	Enthalpy of gas ($kJ\ kg^{-1}$)
h_1	Enthalpy at evaporator inlet ($kJ\ kg^{-1}$)
h_2	Enthalpy at evaporator outlet ($kJ\ kg^{-1}$)
I	Current (Amp)
K_e	Equivalent spring constant ($N\ m^{-1}$)
L_e	Inductance of coil (Henry)
l_e	Effective length of coil (m)
m	Mass flow rate of gas (kg s-1)
M_p	Resonating mass of the system (kg)
n	Number of cycles
P	Pressure (Pa)
RE	Refrigerating Effect (kW)
Rho	Density ($kg\ m^{-3}$)
R_e	Resistance of the coil (Ohm)
T	Temperature of gas
T_e	Temperature at evaporator (^oC)
Tc	Temperature at condenser (oC)
t	Time (sec)
V	Cylinder Volume (m3)
Ve	Supply or source voltage (Volt)
V_0	Initial value of voltage (Volt)
W	Compressor Work supplied (W)
x	Stroke of the piston (m)
$\dot{x}$	Velocity of the piston (m s-1)
$\ddot{x}$	Acceleration of piston (m s-2)

Subscripts

cl	Clearance
cyl	cylinder
dv	Discharge valve
dis	Discharge
e	Effective
in	Inside cylinder
out	Leaving cylinder
p	Piston
sub	Sub-cool
suc	Suction
sup	Superheat
sv	Suction valve

1. Introduction

A Linear compressor has one of the highest efficiency's compared to other available compressors. In a linear compressor there is an oscillating motor and a piston rigidly coupled to it. The linear motors can be classified as moving coil, moving iron and moving magnet types. Oscillations of the linear motor are directly transferred to the piston. Working of linear compressor is similar to the reciprocating compressor i.e. suction and compression alternately. Because of absence of the crank and the connecting rod mechanism in the linear compressor, there are less friction losses and mechanical efficiency of the linear compressor is greater. Lee et al. (2004) reported the importance of linear compressor for air conditioning systems. This paper reports the potential of the mathematical model developed by the authors and review of various parameters. Pollak et al. (1978) created a mathematical model explaining major characteristic of the oscillatingelectrodynamic compressor which has been proved experimentally. The relation between efficiency with driving frequency and pressure ratio with mass flow rate has been presented. Liang et al. (2014) compared crank-drive reciprocating compressor with oil free linear compressor. Nitrogen was used as a refrigerant in the experiment. The motor performance and overall efficiencies of two compressors are discussed. At low power inputs, the motor efficiency of the moving magnet linear compressor is greater than that of conventional induction motor used in the crank-drive reciprocating compressor. The Linear compressor has been developed for vapour compression systems and reported. [5-12]. Craig et al. (2013a, 2013b) worked on detailed analysis of linear compressor for electronics cooling, energy recylying, and its advantages.

A complete analysis of linear compressor can be achieved with the help of Mathematical model developed. The flowchart of the simulation of the model is shown in Figure 1. The mathematical model predicts instantaneous properties. Interfacing of the program is done with refrigerant property software i.e. REFPROP. Input of ny two refrigerant properties has to be given in the software and the rest are called out by the software itself. The user can create his/her own refrigerant mixtures and understand the different properties.

1.1 Equations considered for developing the model

Equations required describing the linear compressor characteristics are:

A) Motor Equation Integrating the equation for di/dt w.r.t. time gives instantaneous current which is the output.

B) Piston Dynamics [$〖M〗\_p\ (x)/dt + C\_p\ dx/dt + K\_e\, x = F$]

These equations are solved by Runge-Kutta 4th order method of integration.

C) Pressure value is estimated by the refrigerant property software REFPROP (NIST)

D) Valve dynamics and mass flow estimation

2. Validation of mathematical model

The validation of the mathematical model is done by comparing its outputs with the data reported by Lee et al. (2004) for the 1-litre air conditioner. The input parameters to the model are listed in Table 1. The model follows the ASHRAE-T conditions for testing with therefrigerant R410A. The comparison of the output parameters is presented in Table 2, which shows close agreement with each other.

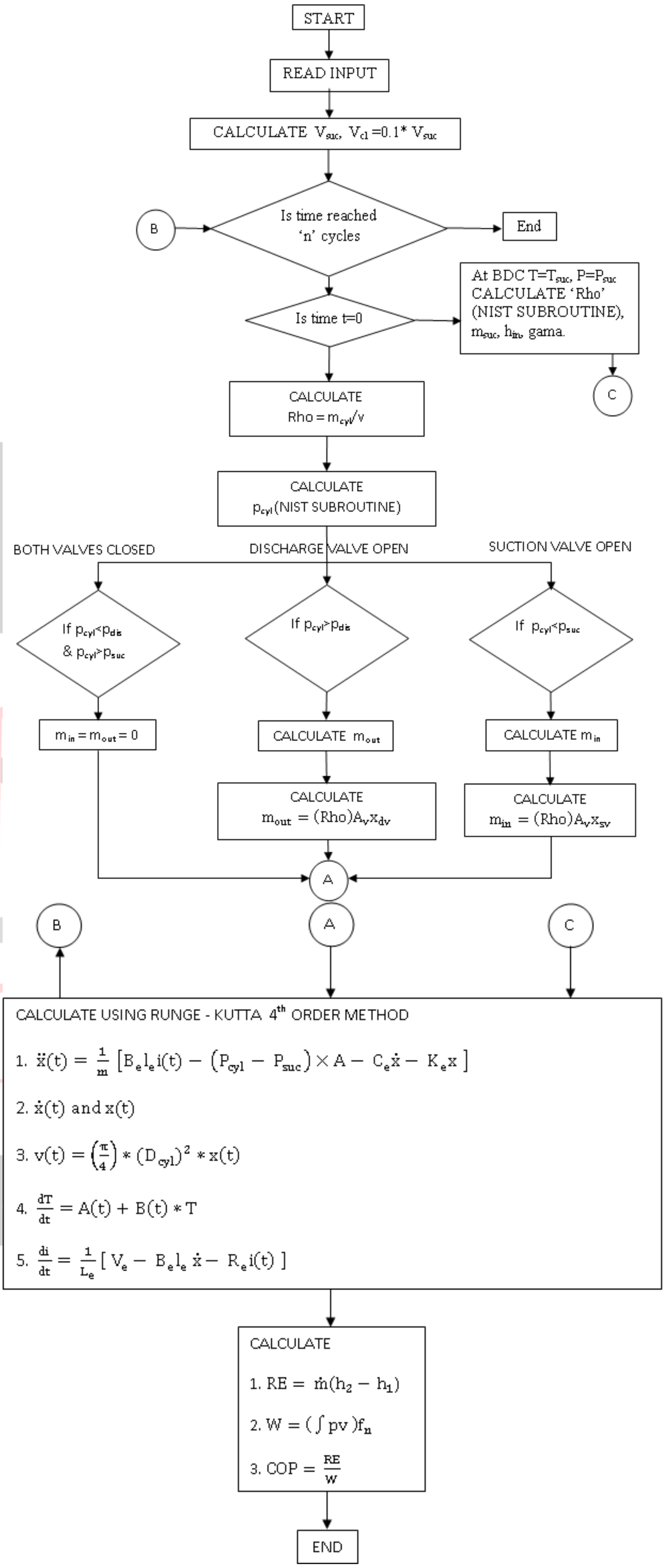

Figure 1. Flow chart for Mathematical model

Table 1. Input parameters to mathematical model for validation

Table 2. Comparison of model Estimated and Reported Data by Lee et al. (2004).

Parameter	Value	Parameter	Value
Frequency (f_n, Hz)	60	Spring Stiffness (K_e, N m^{-1})	266162
Max Piston stroke (x(t), mm)	35	Input Voltage (V_e, Volt)	226.5
Cylinder diameter (D, mm)	20	Evaporator Temperature (T_e, °C)	7.2
Length of coil (L_e, m)	53.5	Condenser Temperature (T_c ,°C)	54.4
Effective magnetic flux (B_e, Wb m^{-2})	0.8	Sub-cooled Temperature (T_{sub}, °C)	46.1
Motor Efficiency (η, %)	92	Superheated Temperature (T_{sup}, °C)	27.8
Moving mass (m_p, kg)	2.1	Cooling Capacity (kW)	3.5

3. Parametric analysis of linear compressor

There are various parameters which affect the performance of the linear compressor. The work presented here shows effect of following parameters on the performance of the compressor,

- Voltage (Vo)
- Refrigerant: (R600a, R134a ,R404A)
- Superheat Temperature (Tsup)

	Parameter	Mathematical model results	Reported Data	Discrepancy (%)[a]
1	Refrigerant	R410A	R410A	-
2	Operating Frequency (Hz)	60.00	60.00	-
3	Cooling Capacity (kW)	3.53	3.51	0.57
4	Compressor Power (kW)	0.92	0.96	- 3.75
5	COP	3.80	3.60	5.56
6	Theoretical efficiency (%)	67.70	61.70	9.2

[a]100(Model result – Lee et al. reported value) / Lee et al. reported value

For each following section, one parameter is varied keeping all other parameters constant and its effect on compressor performance is studied. Intensive parametric analysis has been carried out to understand the effect of various parameters on the performance of the compressor.

The geometrical parameters of the compressor are taken from the market available compressor for air conditioning application. The stroke and Bore of the compressor are 10 mm and 22.5mm respectively. The moving mass (Mp) is 0.85 kg, spring stiffness is 85000 N/m. The theoretical properties are taken from ASHRAE-T conditions for air conditioning i.e. evaporator temperature (Te) 7.22oC and condenser temperature (Tc) 54.45oC. The suction pressure (Psuc) and discharge pressure (Pdis) are taken by considering saturated pressure values of refrigerants with respect to evaporative and condensing temperature. The working frequency (as per the supply condition of India) is 50 Hz.

3.1 Effect of voltage(V_o) on the functioning of the compressor

There is constrained piston motion in a traditional reciprocating compressor while the linear compressor is a free piston machine. The amplitude of the piston is dependent on the input voltage. The current drawn by the linear motor rises(Refer equation 1 and 2) when the input voltage increases causing a rise in the stroke of the piston(Refer Figure 3).R134a is the refrigerant used for the simulation. Voltage (V_o) is changed from 75 V to 100 V in steps of 5V.It can clearly be understood from Figures 2 and 3 wherein current and piston stroke are plotted against time with changing voltage that there is variation in current drawn and ultimately the motor force (*B* i*l*), which is the driving force of the piston travel (resulting in a rise in the piston stroke) due to change in supply voltage while maintaining the same motor resistance. Consequently, the piston has to move with higher velocity as the stroke increases with rise in input voltage and the frequency of the current is also constant. It can be seen from Figure 4 that the piston velocity is maximum at 100 and minimum at 75 volts. Fig. 5 depicts the nature of change in volume of the compressor cylinder.

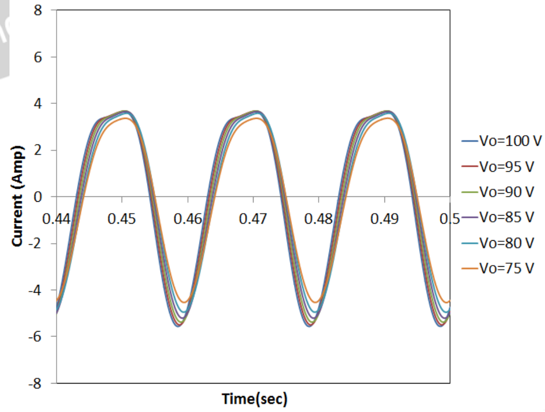

Figure 2. Motor Current (Amp) v/s Time (sec)

Table 3. Effect of voltage on compressor performance

Parameters	Input Voltage Vo (Volts)					
	75	80	85	90	95	100

1	Cooling Capacity (W)	0.00	27.75	150.65	292.53	449.73	621.50
2	Compressor Power (W)	0.20	6.50	35.62	69.26	106.50	147.14
3	Coefficient of Performance	0.00	4.26	4.22	4.22	4.22	4.22
4	Theoretical Efficiency (%)	0.00	71.88	71.22	71.14	71.13	71.15
5	Volumetric Efficiency (%)	27.28	36.50	44.61	53.36	62.30	71.24

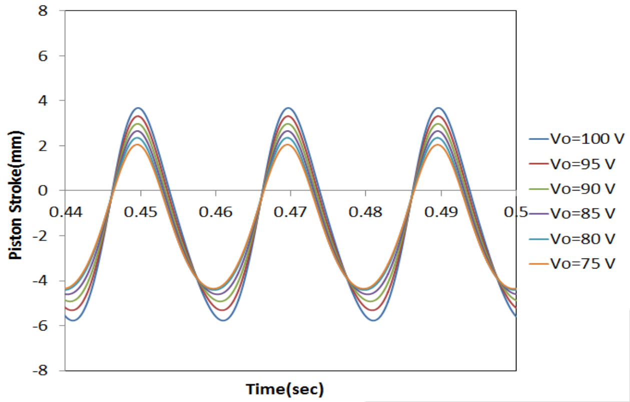

Figure 3. Piston Stroke (mm) v/s Time (sec)

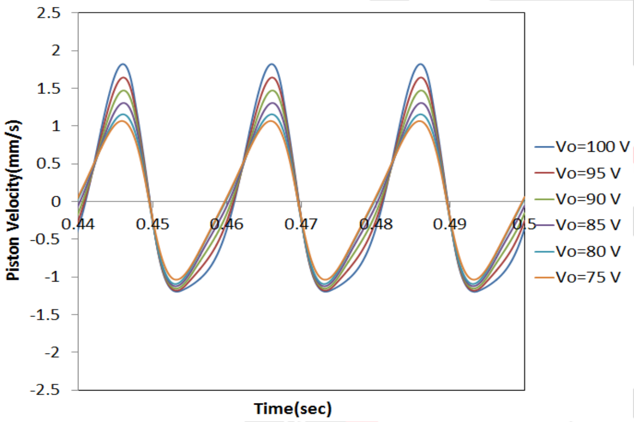

Figure 4. Piston Velocity (mm/s) v/s Time (sec)

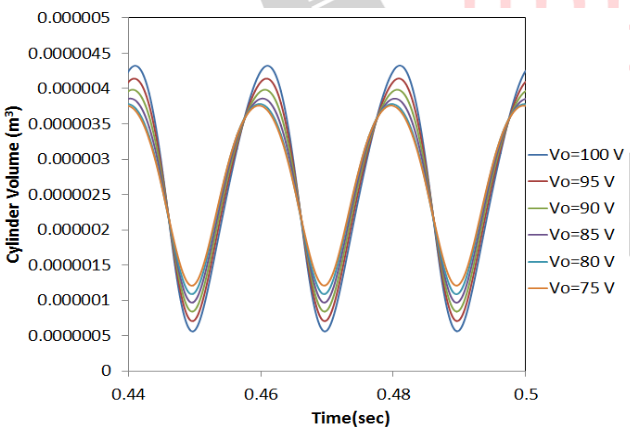

Figure 5. Cylinder Volume (m³) v/s Time (sec)

The work needed by the compressor per cycle is estimated by the pressure-volume diagram. With an increase in voltage from 75 to 100 V, the amplitude of the piston stroke also rises. The rise in voltage results in an increase in the stroke as demonstrated in Figure 3, causing an increase in the volume covered by the piston(Refer Figure 5).Therefore it can be seen on the P-V curve that there is an increase in the P-V area(Refer Figure 6) as the x-coordinate (compressor volume) traced by the piston increases .Also, the mass delivered by the compressor increases as the swept volume increases. For that reason, higher the mass discharged by the compressor, higher will be the heat absorbed in the evaporator ,that is, there will be rise in cooling capacity(Refer Table 3).It can be projected from Figure 6 that with rising voltage the P-V area increases and therefore the work required by the compressor per cycle increases.

Table 3 illustrates that cooling capacity increases with an increase in voltage. Hence the influence of voltage on COP of the system is trivial as there is simultaneous rise in compressor power. The changing voltage input to the linear compressor can be utilised as a controlling parameter for piston stroke. A unique trait of the linear compressor is the variation of amplitude of piston stroke in accordance with the cooling demand. Table 3 taking into account the case of rise in voltage from 95 to 100 V, the growth in P-V area is 38.41%, resulting in an escalation in the work required by the compressor. In the same way, for an increase in voltage from 85 to 90V and from 90 to 95 V, the growths in P-V areas (ultimately work required) are 53.77% and 94.77% respectively.

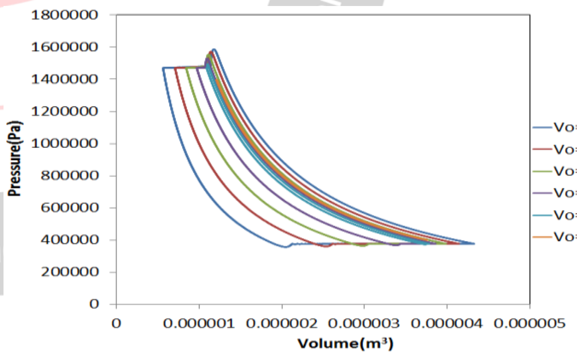

Figure 6. Pressure (Pa) v/s Volume (m³)

3.2 Effect of refrigerant on the performance of compressor

The vapor-compression cycle uses a circulating liquid refrigerant as the medium which absorbs and removes heat from the space to be cooled and subsequently rejects that heat in the condenser. Refrigerant flows through the compressor, which raises the pressure of the refrigerant. At the ASHRAE-T condition condenser temperature (54.4 ^oC) and evaporator temperature (7 ^oC) remain the same, but as the refrigerant changes saturation pressure changes accordingly. Hence discharge and suction pressure for each refrigerant for same condensing and evaporator temperature vary for different refrigerants.

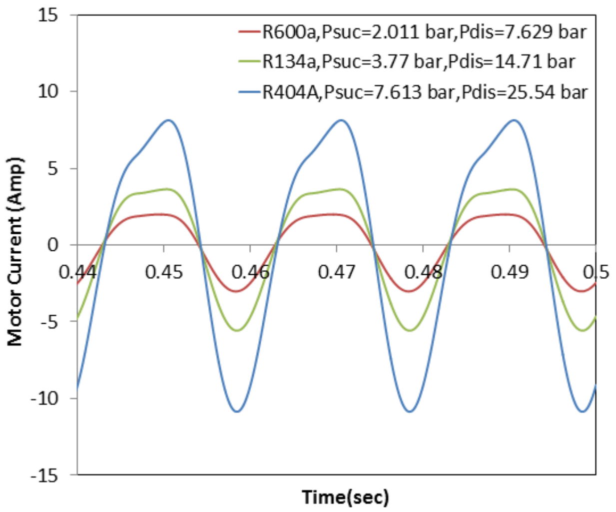

Figure 7. Motor Current (Amp) v/s Time (sec)

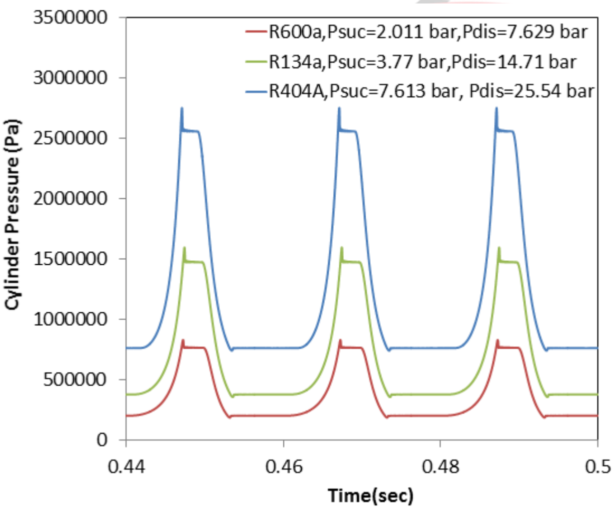

Figure 8. Cylinder Pressure (Pa) v/s Time (sec)

There are various types of refrigerant available in the market for the refrigeration application. The refrigerants considered in this work are R600a, R134a, and R404A.The behavior of all parameters of the compressor will be influenced by the saturation pressures of refrigerants at given condenser and evaporative temperatures. The discharge pressure required for R404A is more as compared to remaining refrigerants, so the current drawn is also more for R404A as shown in Figure 7. Suction and discharge pressures for different refrigerants are different, resulting in variation in pressure ratio as shown in Figure 8. As the discharge pressure increases from R600a to R404A the driving force required by the piston to compress the same volume of gas increases with increasing in discharge pressure. The required increase in driving force is compensated by a linear motor drawing more current.

The Pressure-Volume diagram is used to calculate work required by compressor per cycle. The P-V area increases mean work required by compressor per cycle is more as shown in Figure 9. This results increase in cooling capacity with the increase in pressure difference.

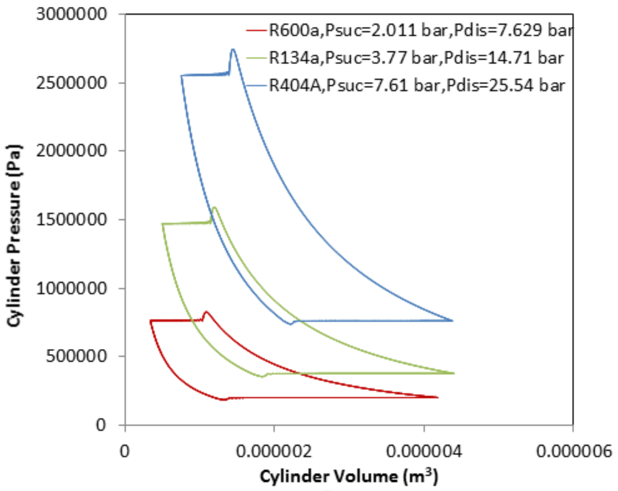

Figure 9. Cylinder Pressure (Pa) v/s Volume (m³)

3.3 Effect of superheat temperature on the performance of the compressor

To examine the effect of superheat temperature on performance of the compressor, superheat temperature is varied from 5˚ to 25˚, keeping all other parameters constant.

Table 4. Effect of superheat temperature on compressor performance.

Parameters		**$T_{superheat}$(°C)**		
		5	**15**	**25**
1	Cooling Capacity (W)	688.30	697.20	706.54
2	Compressor Power (W)	165.26	163.72	162.57
3	Coefficient of Performance	4.16	4.25	4.34
4	Theoretical Efficiency (%)	70.16	71.73	73.21
5	Volumetric Efficiency (%)	74.90	74.66	74.45

The refrigerant R134a is used and voltage at input is 102V.From table 4 we come to know that as superheating temperature increases COP, cooling capacity and EER of the system increases and at same time compressor power decreases. The cooling capacity increases by 2.65% and power reduces by 1.26% as the superheat temperature increases from 5˚to 25˚. Due to this combined effect of increase and decrease in cooling capacity and compression power respectively, COP of system increases by 4.32%.

4. Conclusions

In this paper, behaviour of linear compressor is validated using mathematical model and it is validated to the experimental data. Various parametric analyses are carried out i.e. by varying input voltage, refrigerant and superheat temperature.

(1) Results from the mathematical model agree well with the data from experiment.
(2) A unique feature of variable capacity performance by changing the input voltage of the linear compressor is presented.
(3) Effects of various refrigerants used and variable superheating temperatures are also presented.

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