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Testing and Comparison of Capacity Control Methods for Helical Screw Compressor

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Abstract—The most important factor associated with compressed air is the consumption of energy required to drive the compressor. When consumption of energy is considered, it becomes very important that capacity control methods are implemented. To select the best method, a comparison between the various capacity control methods was carried out in a well known compressor manufacturing company in Pune. The paper deals with the comparison of the various capacity control methods for helical screw compressor.
Comparison between,

1. ***On – Off method***
2. ***Loading/Unloading method***
3. ***Modulation Control***
4. ***Variable Frequency Drive method***

was carried out by plotting graphs of ' Power consumed versus FAD (free air delivery)'

Keywords—Capacity Control, On-Off Method, Loading Unloading method, Modulation Control method, Variable Frequency Drive method.

I. INTRODUCTION

In industry, compressed air requirement varies as per the need of the application. Different applications in industries have different demands, installing individual compressor to satisfy each demand is expensive both installation and maintenance wise. So, Capacity Control methods are adopted to overcome this problem of fluctuating demand.

Problem Definition: To find the most efficient method for the capacity control of compressors out of,

1.) On- off method
2.) Loading/unloading method
3.) Modulation control
4.) Variable Frequency Drive method

II. VARIOUS CAPACITY CONTROL METHODS

1. On – Off method: When pressure reaches an upper pre-set limit, the compressor motor gets turned off and no further air is compressed. When pressure drops to a predetermined lower limit, the motor starts and the cycle is repeated.

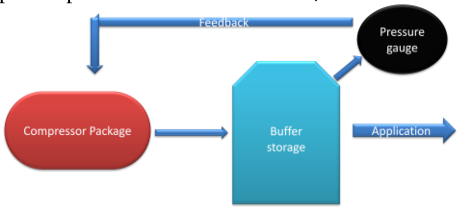

Figure- 1: On Off Method

2. Loading Unloading method: The compressor motor continues to run even while the compressor operates in an unloaded mode. The capacity is controlled by the complete opening and closing of inlet valve.

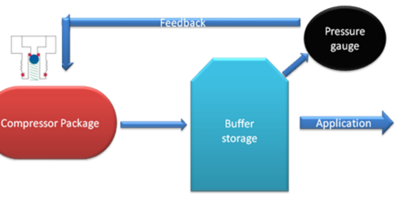

Figure- 2: Loading Unloading Method.

3. Modulation method: In this method, the modulation valve varies the inlet volume as per the requirement. It acts like a throttle valve. The inlet valve opens/closes partially to meet the demand.
4. Variable Frequency Drive method: The frequency of the motor is directly proportional to the free air delivery (FAD) of the compressor. Hence by varying the frequency of the motor, the FAD can be varied and demand can be satisfied. This is the most efficient method.

III. THEORETICAL CALCULATIONS TO FIND POWER CONSUMPTION

We know that time required for receiver to go from upper to lower pressure limit is given by-

$$t = \frac{V(P1 - P2)}{q \times Pa}$$

where,

V = Volume of the receiver tank (m^3)

t = Time for the receiver to go from upper pressure limit to lower pressure limit (sec)

q = Free air flow (FAD) (m^3/min)

Pa = Atmospheric pressure (bar)

P1= Maximum tank pressure (bar)

P2 = Minimum Tank Pressure (bar)

Theoretically, we assumed that compressor receiver is initially at upper pressure limit and calculated the time required for receiver to go from upper pressure limit to lower pressure limit for different FAD percentages. Based on the time required, power required to compress the air can be found out.

The graph of 'Power Consumed vs FAD' shows the most efficient method of capacity control.

For all methods we have taken readings on a compressor coupled to 55kW motor.

Considering,
Receiver volume V= $1m^3$.
Maximum receiver pressure P1= 8 bar.
Minimum receiver pressure P2 = 7 bar.
Maximum FAD q= 10.85 m^3/min = $0.181m^3$/sec.
Atmospheric pressure Pa= 1.01325 bar.
Time required for receiver to from upper pressure limit to lower pressure limit at 100% FAD (i.e. for 1st reading) is

$$t = \frac{V(P1-P2)}{q \times Pa} = \frac{1\times(8-7)}{(0.01\times100\times0.181)\times1.01325} = 5.457 \text{ sec}$$

Sr.no	V (m^3)	P_1 (bar)	P_2 (bar)	% of outlet air required relative to FAD	Q (m^3/min)	P_a (bar)	Unload Time T (sec)
1	1	8	7	90	10.85	1.01325	6.06
2	1	8	7	80	10.85	1.01325	6.82
3	1	8	7	70	10.85	1.01325	7.79
4	1	8	7	60	10.85	1.01325	9.09
5	1	8	7	50	10.85	1.01325	10.91
6	1	8	7	40	10.85	1.01325	13.6
7	1	8	7	30	10.85	1.01325	18.19
8	1	8	7	20	10.85	1.01325	27.28
9	1	8	7	10	10.85	1.01325	54.57

Table: 1 Theoretical time calculation.

1. On-Off method calculations: Maximum Power consumed at 100% FAD is 55000 × 1.15 = 63250 W
Power consumed,

$$P = \frac{(Total\ power \times load\ time) + (Total\ power \times motor\ efficiency \times unload\ time)}{(load\ time + unload\ time)}$$

For On-Off Method					
Sr.no	% FAD	Load Time (sec)	Unload Time (sec)	Power Consumed (W)	% Power Consumed
1	10	5.45	54.57	5749.3	9.08
2	20	6.06	27.28	11499.9	18.18
3	30	6.82	18.19	17249.9	27.27
4	40	7.79	13.64	22998.8	36.36
5	50	9.09	10.91	28749.8	45.45
6	60	10.95	9.09	34499.5	54.54
7	70	13.64	7.79	40249.8	63.63
8	80	18.19	6.82	45999.9	72.72
9	90	27.28	6.06	51749.9	81.8
10	100	54.57	5.45	57499.9	90.9

Table: 2 Theoretical Power Calculations

2. Load Unload Method Calculations:

For Load-Unload Method					
Sr. No	% FAD	Load Time (sec)	Unload Time (sec)	Power Consumed (W)	% Power Consumed
1	10	5.45	54.57	22999.59	36.36
2	20	6.06	27.28	27025	42.727
3	30	6.82	18.19	31050	49.09
4	40	7.79	13.64	35074.24	55.45
5	50	9.09	10.95	39100.20	61.81
6	60	10.95	9.09	43124.79	68.18
7	70	13.64	7.79	47150.7	74.54
8	80	18.19	6.82	51175	80.90
9	90	27.28	6.06	55200	87.27
10	100	54.57	5.45	59225.40	93.63

Table: 3 Theoretical Power Calculations

3. Modulation Method:

Modulation technique is independent of load and unload times. Modulation valve changes the FAD as per the application requirement.
Power consumed,

$$P = \frac{\gamma}{\gamma-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

where,
P1 = 1.01325 bar (atmospheric pressure)
P2 = 8 bar (receiver upper pressure)
γ = 1.4 (adiabatic index)
V1 = inlet volume (FAD) = 10.85 m^3/min = 0.181m^3/sec.

Modulation Method			
Sr. No	%FAD	Power Consumed (W)	% Power Consumed
1	10	15848.51	25.05
2	20	23718.63	37.49
3	30	29601.56	46.80
4	40	34349.94	54.30
5	50	38324.50	60.59
6	60	41721.57	65.96
7	70	44663.26	70.61
8	80	47232.15	74.67
9	90	49487.42	78.24
10	100	51473.38	81.38

Table: 4 Theoretical Power Calculations

4. Variable Frequency Drive Method:

The maximum Power will be consumed at 50Hz supply frequency, at which we get 100% FAD at outlet.

FAD (V_1) = swept volume (V_s) × RPM

RPM (N) = $\frac{120\times f}{P}$

Where, f = frequency Hz.

P = number of poles = 2.

In adiabatic power consumption, only V_1 is variable.

∴ $P = K_1 \times f$

Where,

$K_1 = \frac{\gamma}{\gamma-1} \times P_1 \times \left[\left(\frac{P2}{P1}\right)^{\gamma-1/\gamma} - 1\right] \times \frac{Vs\times 120}{P}$

where,

$\gamma = 1.4$

P_1 = atmospheric pressure = 1.01325 bar.

P_2 = required pressure = 8 bar.

V_s = swept volume = 2.92×10^{-3} m^3/rev.

P = number of poles = 2

Adiabatic Power consumption			
Sr. No.	frequency	Power (W)	% Power consumption
1	5	249119.82	10
2	10	498239.64	20
3	15	747359.46	30
4	20	996479.28	40
5	25	1245599.10	50
6	30	1494718.92	60
7	35	1743838.74	70
8	40	1992958.56	80
9	45	2242078.38	90
10	50	2491198.20	100

Table: 5 Adiabatic Power Calculations

Motor Power Consumption			
Sr. No.	Frequency	Power (W)	% Power consumption
1	5	6325	10
2	10	12650	20
3	15	18975	30
4	20	25300	40
5	25	31625	50
6	30	37950	60
7	35	44275	70
8	40	50600	80
9	45	56925	90
10	50	63250	100

Table: 6 Theoretical motor power calculations

Theoretical plot of Power vs FAD

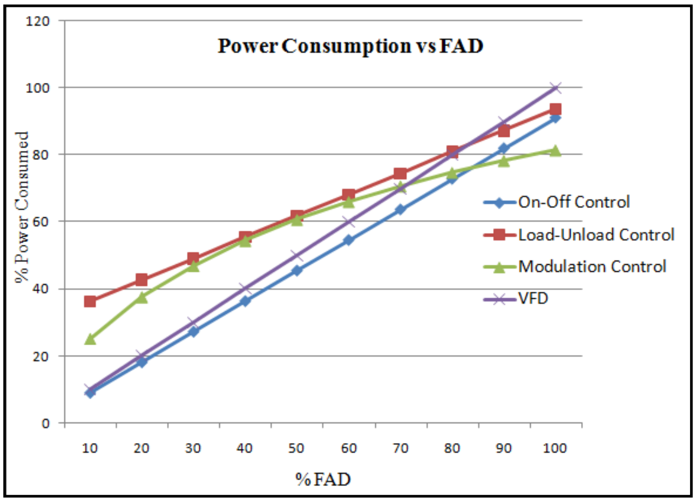

Figure: 3 Graph: Power Consumption Vs. FAD

IV. EXPERIMENTAL RESULTS AND CALCULATIONS FOR POWER CONSUMPTION

1. On- Off Method:

We consider that when compressor is in unloading state the power consumed by the motor is zero. In calculations, the unloading power has been taken directly as zero.

Reading	1	2	3	4
Reading Time	17:00	18:00	19:00	20:00
1)Atmospheric pressure in mm of Hg.	711.30	711.30	711.30	711.30
2)Atmospheric temp.⁰C	32.0	33.0	33.0	33.0
3)Air Delivery pressure Kg/cm2	7.0	7.0	7.0	7.0
4)After Cooler Outlet Temp.⁰C	41.0	41.0	42.0	42.0
5)Motor RPM	2965	2936	2938	2941
6) Air intake Temp.⁰C	37.0	37.0	37.0	37.0
7)Air Temp.At Nozzle⁰C	39.0	39.0	39.0	39.0
8)Differential pr.at the nozzle in mm of water	290	291	290	291
9)Upstream pr.at the nozzle in mm of water	150	150	149	149
10)Suction Filter Drop in mm of Water	100.0	100.0	100.0	100.0
11)FAD in m3/min.	8.76	8.78	8.76	8.78
12)FAD Corrected at 2945 Rpm	8.86	8.96	8.94	8.95
13)Voltage in volts	440.00	427.00	429.00	430.00
14)Current in ampers	105.50	106.60	107.00	107.00
15)Input Power (kW)	72.1	71.06	71.11	71.21
16)Output Power Kw Corrected at 2945 Rpm	64.05	63.72	63.72	63.75

Table 7: Test report On-Off Method

From the readings 'Free Air Delivery' can be calculated as per IS 10431.

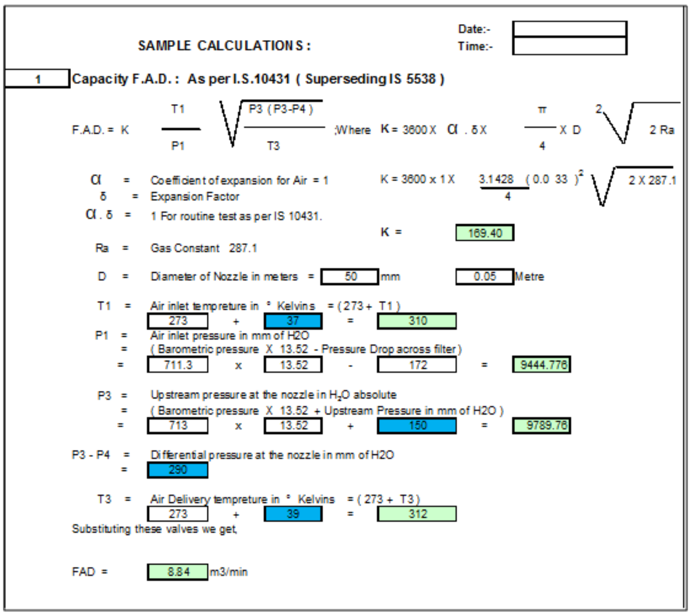
SAMPLE CALCULATIONS :
Date:-
Time:-
1 Capacity F.A.D. : As per I.S.10431 (Superseding IS 5538)
F.A.D. = K (T1 / P1) √(P3 (P3-P4) / T3) ;Where K = 3600 X α . δ X (π / 4) X D² √(2 Ra)
α = Coefficient of expansion for Air = 1
δ = Expansion Factor
α . δ = 1 For routine test as per IS 10431.
K = 3600 x 1 X (3.1428 / 4) (0.0 33)² √(2 X 287.1)
K = 169.40
Ra = Gas Constant 287.1
D = Diameter of Nozzle in meters = 50 mm 0.05 Metre
T1 = Air inlet tempreture in ° Kelvins = (273 + T1)
273 + 37 = 310
P1 = Air inlet pressure in mm of H2O
= (Barometric pressure X 13.52 - Pressure Drop across filter)
= 711.3 x 13.52 - 172 = 9444.776
P3 = Upstream pressure at the nozzle in H_2O absolute
= (Barometric pressure X 13.52 + Upstream Pressure in mm of H2O)
= 713 x 13.52 + 150 = 9789.76
P3 - P4 = Differential pressure at the nozzle in mm of H2O
= 290
T3 = Air Delivery tempreture in ° Kelvins = (273 + T3)
273 + 39 = 312
Substituting these valves we get,
FAD = 8.84 m3/min

Figure 4: Calculation Sheet: ON-OFF Method.

For plotting the graph and to show the power consumed for different FAD values we consider the output as some percentage of FAD.

From the experimental results obtained the average power consumed by Motor is

P = 63.81 kW

∴ Motor Power Consumed is given by-

$P = \frac{(63.81\times 7.351)+(63.81\times 0\,)}{7.351+66.162} = 6.381$ kW …for 10% FAD

Similarly, Motor Power for ON-Off method was calculated.

On-Off				
Sr. No.	FAD (m^3/min)	Loading time (sec)	Unloading time (sec)	Power Consumed (kW)
1	0.895	7.351	66.162	6.381
2	1.79	8.27	33.08	12.76
3	2.685	9.451	21.66	19.38
4	3.58	11.027	16.54	25.514
5	4.475	13.232	13.232	31.905
6	5.37	16.54	11.027	38.23
7	6.265	21.66	9.451	44.425
8	7.16	33.08	8.27	51.04
9	8.055	66.162	7.351	57.429

Table 8: Experimental power calculations for ON- OFF method.

Note: Experimental calculations for other methods were carried out in a similar fashion and the results obtained were plotted on a graph of 'Power Consumption vs FAD**'**

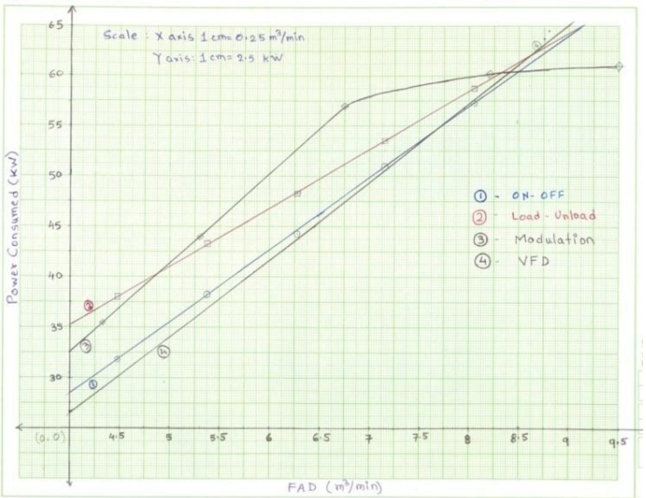

Figure 5: Experimental plot of Power Consumed vs FAD

V. CONCLUSION

1.) It is observed that the nature of experimental plot of 'Power consumed versus FAD' is similar to that of the theoretical plot.
2.) In places where load is comparatively low and compressed air requirement is constant, On-Off method and Load-unload methods are the most suitable one. But the major disadvantage of the On-Off method is high risk of motor failure while the latter does not have.
3.) VFD method and Modulation method can be applied where flow required is not constant but the latter one has more power consumption at low FAD.
4.) Therefore, VFD is the most efficient method for the capacity control in screw compressors.

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