8. ENERGY PERFORMANCE ASSESSMENT OF COMPRESSORS

8.1 Introduction

The compressed air system is not only an energy intensive utility but also one of the least energy efficient. Over a period of time, both performance of compressors and compressed air system reduces drastically. The causes are many such as poor maintenance, wear and tear etc. All these lead to additional compressors installations leading to more inefficiencies. A periodic performance assessment is essential to minimize the cost of compressed air.

8.2 Purpose of the Performance Test

To find out:

- Actual Free Air Delivery (FAD) of the compressor
- Isothermal power required
- Volumetric efficiency
- Specific power requirement

The actual performance of the plant is to be compared with design / standard values for assessing the plant energy efficiency.

8.3 Performance Terms and Definitions

Compression ratio	:	$\frac{\text{Absolute discharge pressure of last stage}}{\text{Absolute intake pressure}}$
Isothermal Power	:	It is the least power required to compress the air assuming isothermal conditions.
Isothermal Efficiency	:	The ratio of Isothermal power to shaft power
Volumetric efficiency	:	The ratio of Free air delivered to compressor swept volume
Specific power requirement	:	The ratio of power consumption (in kW) to the volume delivered at ambient conditions.

8.4 Field Testing

8.4.1 Measurement of Free Air Delivery (FAD) by Nozzle method

Principle: If specially shaped nozzle discharge air to the atmosphere from a receiver getting its supply from a compressor, sonic flow conditions sets in at the nozzle throat for a particular ratio of upstream pressure (receiver) to the downstream pressure (atmospheric) i.e. Mach number equals one.

When the pressure in the receiver is kept constant for a reasonable intervals of time, the airflow output of the compressor is equal to that of the nozzle and can be calculated from the known characteristic of the nozzle.

8.4.2 Arrangement of test equipment

The arrangement of test equipment and measuring device shall confirm to Figure 8.1.

8.4.3 Nozzle Sizes

The following sizes of nozzles are recommended for the range of capacities indicated below:
Flow Nozzle: Flow nozzle with profile as desired in IS 10431:1994 and dimensions

Nozzle size (mm)	Capacity (m^3/hr)
6	3 – 9
10	9 – 30
16	27 – 90
22	60 – 170
33	130 – 375
50	300 – 450
80	750 – 2000
125	1800 – 5500
165	3500 – 10000

8.4.4 Measurements and duration of the test.

The compressor is started with the air from the receiver discharging to the atmosphere through the flow nozzle. It should be ensured that the pressure drop through the throttle valve should be equal to or twice the pressure beyond the throttle. After the system is stabilized the following measurements are carried out:

- Receiver pressure
- Pressure and temperature before the nozzle
- Pressure drop across the nozzle
- Speed of the compressor
- kW, kWh and amps drawn by the compressor

The above readings are taken for the 40%, 60%, 100% and 110% of discharge pressure values.

Measuring instruments required for test

- Thermometers or Thermocouple
- Pressure gauges or Manometers
- Differential pressure gauges or Manometers
- Standard Nozzle

- Psychrometer
- Tachometer/stroboscope
- Electrical demand analyser

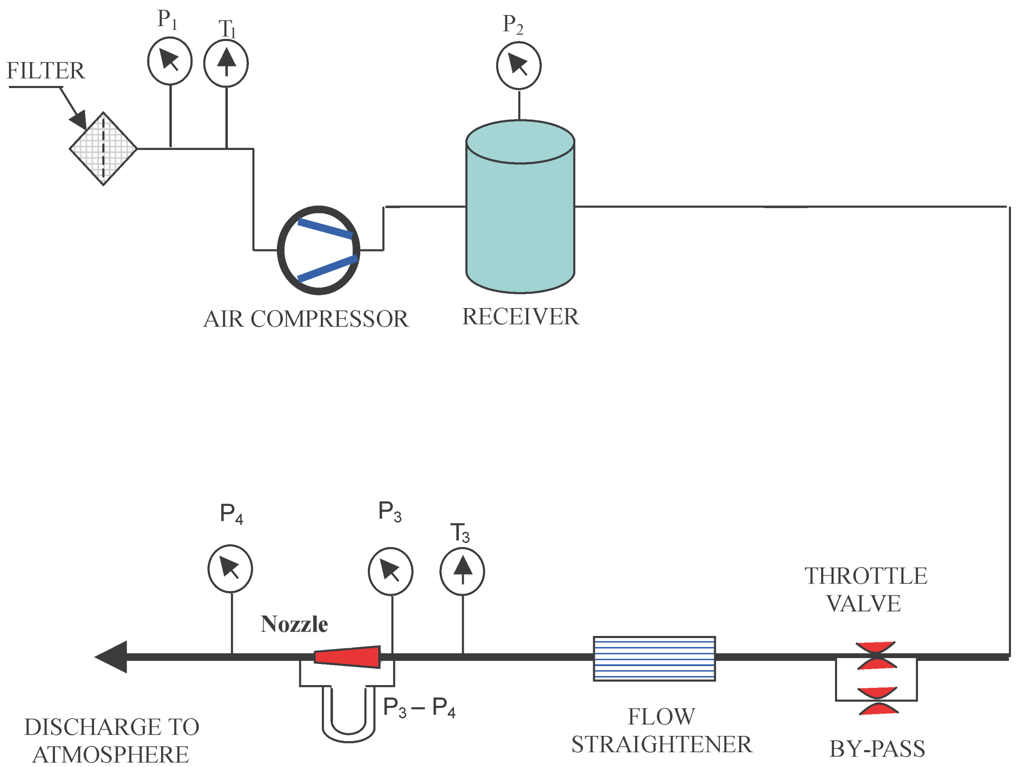

Figure 8.1: Test Arrangement for Measurement of Compressed Air Flow

8.5 Calculation Procedure for Nozzle Method

I. Free Air delivered Q_f in m^3/sec $= k \times \pi \times \frac{d^2}{4} \times \frac{T_1}{P_1} \times \left[\frac{2\,(P_3 - P_4)\,(P_3 \times R_a)}{T_3} \right]^{1/2}$

k	:	Flow coefficient – as per IS
d	:	Nozzle diameter M
T_1	:	Absolute inlet temperature °K
P_1	:	Absolute inlet pressure kg/cm^2
P_3	:	Absolute Pressure before nozzle kg/cm^2
T_3	:	Absolute temperature before nozzle °K
R_a	:	Gas constant for air 287.1 J/kg k
P_3–P_4	:	Differential pressure across the nozzle kg/cm^2

II. Isothermal Efficiency = Isothermal power/Input power

Isothermal power(kW) = $\frac{P_1 \times Q_f \times \log_e r}{36.7}$

P_1 = Absolute intake pressure kg/ cm^2
Q_f = Free air delivered m^3/hr.
r = Pressure ratio P_2/P_1

III. Specific power consumption at rated discharge pressure = $\frac{\text{Power consumption ,kW}}{\text{Free Air Delivered, } m^3/hr}$

IV. Volumetric efficiency = $\frac{\text{Free air delivered } m^3/min \times 100}{\text{Compressor displacement, } m^3/min}$

Compressor Displacement = $\frac{\pi}{4} \times D^2 \times L \times S \times \chi \times n$

D = Cylinder bore, metre
L = Cylinder stroke, metre
S = Compressor speed rpm
χ = 1 for single acting and 2 for double acting cylinders
n = No. of cylinders

8.6 Example

Calculation of Isothermal Efficiency for a Reciprocating Air Compressor.

Step – 1 : Calculate Volumetric Flow Rate

k	:	Flow coefficient (Assumed as 1)
d	:	Nozzle diameter : 0.08 metre
P_2	:	Receiver Pressure – 3.5 kg / cm^2 (a)
P_1	:	Inlet Pressure – 1.04 kg / cm^2(a)
T_1	:	Inlet air temperature 30°C or 303°K
P_3	:	Pressure before nozzle – 1.08 kg / cm^2
T_3	:	Temperature before the nozzle 40°C or 313°K
$P_3 – P_4$	:	Pressure drop across the nozzle = 0.036 kg / cm^2
R_a	:	Gas constant : 287 Joules / kg K

$$\text{Free Air Delivered } Q_f = k \times \frac{\pi}{4} \times d^2 \times \frac{T_1}{P_1} \times \left[\frac{2\,(P_3-P_4)\,(P_3 \times R_a)}{T_3}\right]^{1/2}$$

$$= 1 \times \frac{\pi}{4} \times (0.08)^2 \times \frac{303}{1.04} \times \left[\frac{2 \times 0.036 \times 1.08 \times 287}{313}\right]^{1/2}$$

$= 0.391 \ m^3/sec$

$= 1407.6 \ m^3 / h.$

Step – 2 : Calculate Isothermal Power Requirement

Isothermal Power (kW) $= \dfrac{P_1 \times Q_f \times \log_e r}{36.7}$

P1 - Absolute intake pressure = $1.04 \ kg / cm^2$ (a)

Qf - Free Air Delivered = $1407.6 \ m^3 / h.$

Compression ratio r $= \dfrac{3.51}{1.04} = 3.36$

Isothermal Power $= \dfrac{1.04 \times 1407.6 \times \log_e 3.36}{36.7} =$ **48.34 kW**

Step – 3 : Calculate Isothermal Efficiency

Motor input power = 100 kW

Motor and drive efficiency = 86 %

Compressor input power = 86 kW

Isothermal efficiency $= \dfrac{\text{Isothermal Power} \times 100}{\text{Compressor input Power}}$

$= \mathbf{\dfrac{48.34 \times 100}{86.0} = 56\%}$

8.7 Assessment of Specific Power requirement

Specific power consumption $= \dfrac{\text{Actual power consumed by the compressor}}{\text{Measured Free Air Delivery}}$

In the above example the measured flow is 1407.6 m^3/hr and actual power consumption is 100 kW.

Specific power requirement $= \dfrac{100}{1407.6}$

$= 0.071 \ kW/m^3/hr$

8.8 Measurement of FAD by Pump Up Method

(Note: The following section is a repeat of material provided in the chapter-3 on Compressed Air System in Book-3.)

Another way of determining the Free Air Delivery of the compressor is by Pump Up Method - also known as receiver filling method. Although this is less accurate, this can be adopted where the elaborate nozzle method is difficult to be deployed.

Simple method of Capacity Assessment in Shop floor

- Isolate the compressor along with its individual receiver being taken for test from main compressed air system by tightly closing the isolation valve or blanking it, thus closing the receiver outlet.
- Open water drain valve and drain out water fully and empty the receiver and the pipeline. Make sure that water trap line is tightly closed once again to start the test.
- Start the compressor and activate the stopwatch.
- Note the time taken to attain the normal operational pressure P_2 (in the receiver) from initial pressure P_1.
- Calculate the capacity as per the formulae given below:

Actual Free air discharge

$$Q = \frac{P_2 - P_1}{P_0} \times \frac{V}{T} \text{ Nm}^3/\text{Minute}$$

Where

P_2	=	Final pressure after filling (kg/cm^2 a)
P_1	=	Initial pressure (kg/cm^{2}a) after bleeding
P_0	=	Atmospheric Pressure (kg/cm^2 a)
V	=	Storage volume in m^3 which includes receiver, after cooler, and delivery piping
T	=	Time take to build up pressure to P_2 in minutes

The above equation is relevant where the compressed air temperature is same as the ambient air temperature, i.e., perfect isothermal compression. In case the actual compressed air temperature at discharge, say t_2°C is higher than ambient air temperature say t_1°C (as is usual case), the FAD is to be corrected by a factor $(273 + t_1) / (273 + t_2)$.

EXAMPLE

An instrument air compressor capacity test gave the following results (assume the final compressed air temperature is same as the ambient temperature) - Comment?

Piston displacement	:	16.88 m^3/minute
Theoretical compressor capacity	:	14.75 m^3/minute @ 7 kg/cm^2
Compressor rated rpm 750	:	Motor rated rpm : 1445
Receiver Volume	:	7.79 m^3
Additional hold up volume, i.e., pipe / water cooler, etc., is	:	0.4974 m^3
Total volume	:	8.322 m^3

Initial pressure P_1	:	0.5 kg/cm^2
Final pressure P_2	:	7.03 kg/cm^2
Atmospheric pressure P_0	:	1.026 kg/cm^2,a
Time taken to buildup pressure from P_1 to P_2	:	4.021 minutes
Compressor output m^3/minute	:	$\dfrac{(P_2 - P_1) \times \text{Total Volume}}{\text{Atm. Pressure} \times \text{Pumpup time}}$
	:	$\dfrac{(7.03 - 0.5) \times 8.322}{1.026 \times 4.021} = 13.17$ m^3/minute

Capacity shortfall with respect to 14.75 m^3/minute rating is 1.577 m^3/minute i.e., 10.69 %, which indicates compressor performance needs to be investigated further.

QUESTIONS	
1)	What is meant by Free Air Delivery?
2)	Describe the method of estimating flow by nozzle method.
3)	Describe the method of estimating flow by pump up method.
4)	Define the term isothermal efficiency and explain its significance.
5)	Define the term volumetric efficiency and explain its significance.
6)	How is specific power requirement calculated?

REFERENCES

1. IS 10431:1994: Measurement of airflow of compressors and exhausters by nozzles.
2. IS 5456:1985 code of practice for testing of positive displacement type air compressors and exhausters
3. Compressor performance – Aerodynamics for the user by M Theodore Gresh-Butterworth Heinemann.