CHAPTER 5

COMPRESSOR OPERATING PARAMETERS SELECTION USING FUZZY LOGIC UNDER UNCERTAIN CONDITIONS

The energy consumed by the compressor over a period of time depends on the ratio of the actual consumption of air to the capacity of the compressor during the same time period. The actual air consumption over a period is the sum of the air consumed actually by the pneumatic systems and appliances ($Q_{sys}$), unwanted but unavoidable leakage in the pipelines, fittings and hoses ($Q_{leak}$) and the miscellaneous usages ($Q_{mis}$). In the previous chapters, the consumption over a period of time is considered as constant and the leakage and the miscellaneous usage are not taken into account. But in actual practice, leakage of air is not eliminated completely due to practical conditions and miscellaneous usage of air also exists. A methodology using fuzzy logic to select the operating parameters considering the variation in consumption, leakage and miscellaneous usage is presented in this chapter. This method also can be used to design the parameters of various components of compressed air supply system that to be established.

5.1 PROBLEM DESCRIPTION

The variation in consumption of air by pneumatic systems does not follow a fixed pattern and its randomness depends on the nature of the industry. The variation in the consumption due to miscellaneous usage over a period also has the same nature. Though the leakage is not acceptable,
completely avoiding the leakage becomes difficult and some quantity of leak is found in all the industries. The quantity of leak in terms of percentage of compressed air varies from industry to industry. If the selection is carried out with the assumption of zero leakage, leakage in the future may create insufficient air supply to system and lead to failure of optimisation process. Hence for safety purpose, a small quantity of leakage is considered in the proposed methodology. The effect of individual parameters such as pressure bandwidth and receiver volume on power consumed by air compressor for various levels of leakage, miscellaneous usage, variation in consumption are studied individually using fuzzy logic for various levels of the parameter values. Different values for different levels of leakage, miscellaneous usage and system use variation are considered for analysis. In addition to that, study on the combination of presence or absence of these parameters which can play a vital role in determining the optimum value of other parameters such as pressure bandwidth and receiver size are also carried out. Hence in this study, various levels for individual parameters are considered and various combinations of the parameters are also studied. The proposed method is applied to an industrial situation and the results are discussed.

5.2 FUZZY LOGIC SYSTEM

In fuzzy logic models, information is processed in terms of fuzzy sets, made precise through the definition of an associated membership function. The specific inference is then processed by the fuzzy set combined with fuzzy rules. The fuzzy logic model combines one or more input signals, which are defined by the fuzzy sets, with a collection of fuzzy rules to produce an output that can be compared with actual values in the real world. The advantage of fuzzy logic is that the use of fuzzy logic enables the heuristic rule based technique commonly applied to discrete variables to be extended for use in the continuously variable situation, without significantly
increasing the size of the rule base. The fuzzy methods give good performance in controlling non linear system (Boada et al 2006); and fuzzy logic modelling is a powerful tool for exploring complex problems (Chen et al 2000). In compressed air supply system, if more number of parameters need to be considered which has unpredictable variations or uncertainty or non linearity then the system becomes more complex. In such a situation, fuzzy logic can be used to optimise the compressed air system with an acceptable level of accuracy.

The parameters that can affect the loading time of the compressors viz. the quantity of leakage, the variation in the consumption, leakage, receiver volume and the pressure bandwidth are considered for fuzzy based analysis. The Fuzzy Inference System (FIS) used for this study is shown in Figure 5.1, in which the measured values of operating pressure bandwidth ($P_{max}$), system consumption ($Q_{sys}$) and leakage consumption ($Q_{leak}$) receiver volume ($V_r$) and miscellaneous consumption ($Q_{mis}$) are used as input variables. The output is the power consumed by air compressor. The fuzzy control process involves three basic steps: (i) fuzzification, (ii) inference and (iii) defuzzification. They are discussed in the following sections.

5.2.1 Fuzzification

This activity involves the fuzzification of input variables, i.e., converting a crisp value of an input variable into a fuzzy set to make it compatible with a fuzzy set representation of the input variables in the fuzzy rule antecedents. To enable these crisp inputs into their corresponding fuzzy inputs, their membership functions are determined first.
The membership value is represented by a real number ranging between 0 and 1. The fuzzy membership function can be described as follows:

\[ K = \{ (x, \mu_K(x)) | x \in K, \mu_K(x) \in [0,1] \} \] (5.1)

where \( \mu_K(x) \) is the membership function specifying the grade of degree for any element \( x \) in \( K \) which belongs to the fuzzy set \( K \). The larger values of \( \mu_K(x) \) indicate the higher degrees of membership. To provide enough rule coverage, required numbers of fuzzy sets are used for both inputs and outputs. To obtain fast calculation results, triangular shaped membership functions are used for inputs and outputs.

For the application of compressed air supply system, the membership functions are divided into three or five regions, which are linguistically labeled as: Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH). As an example, in Figure 5.2, where an input variable operating pressure bandwidth \( (P_{\text{max}}) \) is fuzzified to Low (L) at \( U_L \) degree of membership and to Very Low (VL) at \( U_{VL} \) degree of membership. Another input variable receiver volume \( (V_r) \) is fuzzified to High (H) at \( U_H \) degree of membership and to Very High (VH) at \( U_{VH} \) degree of membership.
5.2.2 Inference

A fuzzy inference is used to determine the fuzzy output which is based on fuzzy rules and the membership degrees of the fuzzy inputs. The fuzzy rule base consists of linguistic relations between input variables and output variables which are designed by a collection of if-then rules. Based on input and output variables, required numbers of set of rules are developed for this system as shown, graphically in Table 5.1.

![Fuzzification of pressure bandwidth and receiver volume](image)

**Figure 5.2** Fuzzification of pressure bandwidth and receiver volume

<table>
<thead>
<tr>
<th>Operating pressure Bandwidth ((P_{\text{max}}))</th>
<th>VL</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver volume ((V_r)) measured</td>
<td>VL</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>VH</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating pressure ((P_{\text{max}}))</th>
<th>VL</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver volume ((V_r))</td>
<td>VL</td>
<td>L</td>
<td>M</td>
<td>H</td>
<td>VH</td>
</tr>
</tbody>
</table>

**Table 5.1 Fuzzy rule base**

- **Operating pressure Bandwidth (\(P_{\text{max}}\))**
  - VL
  - L
  - M
  - H
  - VH

- **Receiver volume (\(V_r\))**
  - VL
  - L
  - M
  - H
  - VH

- **Fired rule**
The example rules are in the form:

Rule 1:  **IF** operating pressure bandwidth \((P_{\text{max}})\) **IS** VL  
**AND** receiver volume \((V_r)\) **IS** VH  
**THEN** possibility of power consumption **IS** VL

Rule 2:  **IF** operating pressure bandwidth \((P_{\text{max}})\) **IS** M  
**AND** receiver volume \((v_r)\) **IS** M  
**THEN** possibility of power consumption **IS** M

Rule 3:  **IF** operating pressure bandwidth \((P_{\text{max}})\) **IS** VH  
**AND** receiver volume \((V_r)\) **IS** VL  
**THEN** possibility of power consumption **IS** VH etc.

Based on the set of rules, few rules can be identified which can give optimum solutions. These rules are called as fired rules.

### 5.2.3 Defuzzification

The defuzzification activity converts the inferred fuzzy results into the crisp values. The defuzzification method used in this work is based on “the centre of area” method and the defuzzification outputs are the expected power consumption for the given operating parameter values. It yields

\[
z = \frac{\sum_{j=1}^{n} \mu_c(Z_j)Z_j}{\sum_{j=1}^{n} \mu_c(Z_j)} \tag{5.2}
\]

where \(z\) is the crisp output, \(n\) is the number of quantization levels of the output, \(Z_j\) is the amount of control output at the quantization level \(j\) and \(\mu_c(Z_j)\) represents its membership value in the fuzzy output set.
5.3 APPLICATION OF METHODOLOGY TO AN INDUSTRIAL PROBLEM

The proposed method had been applied to a textile industry manufacturing yarns and various combinations of the parameters were also studied. Air has been supplied to its various sections by a 7.5 kW compressor, which has a free air delivery (FAD) of 0.925 SCMM. The compressor is having a receiver volume of 0.5 cubic meters. Plant requirement is 5.5 bar maximum and the operating pressure bandwidth of the compressor has been set at 6 bar to 9 bar. The air leakage in the plant has been estimated from the initial data collection as 17% of the compressor output. The consumption varies from 0.42 SCMM to 0.84 SCMM over a period of time. The trend of air consumption variation as measured is shown in Figure 5.3.

![Figure 5.3 Consumption Variation](image)

The identification of the optimum parameters is carried out and discussed in the following sections, for various combinations of the
parameters such as maximum operating pressure, receiver volume, system consumption, miscellaneous usage and leakage.

5.4 OPTIMISATION BY CONSIDERING TWO PARAMETERS

Two parameters, which are considered in the previous chapters i.e. operating pressure bandwidth \(P_{\text{max}}\) and receiver volume \(V_r\) are taken into consideration to study their effects first.

5.4.1 Fuzzification

The membership functions for these two parameters have been divided into five regions, which are linguistically labelled as: Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH) for both the variables. The membership function editor in the fuzzy toolbox of MATLAB software has been used to display and edit all the membership functions associated with all of the input and output variables for the entire fuzzy inference system. Figure 5.4 shows the membership function editor, where an input variable operating pressure bandwidth \(P_{\text{max}}\) is fuzzified to different degrees of membership function. Same way, it is done for receiver volume \(V_r\) also.

5.4.2 Inference

For the inference purpose, based on input and output variables, twenty five set of rules as explained in section 5.2.2 have been developed, using the rule editor in the same software, for this system as shown graphically in Figure 5.5. The Rule editor is used for editing the list of rules that defines the behaviour of the system. From the above selected set of rules one fired rule can be identified, which give the optimum solution for the values of parameters.
Figure 5.4 The Membership function editor

Figure 5.5 The Rule editor
5.4.3 Defuzzification

Defuzzification is carried out to convert the identified optimum values of the parameters into crisp values. Figure 5.6 shows the rule viewer from which the optimum crisp values can be seen.

![Rule viewer](image)

Figure 5.6 The Rule viewer

5.4.4 Results and discussion

In accordance with the fuzzy rule table developed, the fuzzy reasoning module generates the output map for operating pressure bandwidth ($P_{\text{max}}$) and receiver volume ($V_{r}$). When the operating pressure bandwidth is VL (Very Low) and receiver volume is VH (Very High), the power consumed by the compressor is VL (Very Low), which is evident from the Figure 5.5. The result gives a range of pressure and different receiver sizes that could result in very low power consumption.
This is because, the pressure though at minimum level requires less power, it is not possible to operate the compressor in one pressure value and it requires a range. The range identified so can be appropriately fixed depending on the industry and its operating conditions. For example, the industry with less fluctuation in terms of surging demand can be fixed with Very Low pressure bandwidth and Very High size of receiver. The power consumption by the air compressor at different receiver size and different pressure value conditions are shown in Figure 5.7.

![Figure 5.7 Power consumption for various receiver volume and $P_{\text{max}}$](image)

Power consumption with respect to operating pressure bandwidth ($P_{\text{max}}$) and receiver volume ($V_r$), shows that the power consumed by the compressor decreases when the size of the receiver in the compressed air supply system increases and when the pressure bandwidth in the compressed air supply system decreases. The fuzzy reasoning module developed to
identify the optimum values of pressure bandwidth and receiver volume for any specific industry need, can be used for industries with reasonable savings in energy consumption. From the simulated result it is found that, the reduction in operating pressure bandwidth and increase in the receiver size identified using fuzzy logic minimises the power consumed by compressed air supply system.

5.5 OPTIMISATION BY CONSIDERING THREE PARAMETERS

The variables \( P_{\text{max}} \), \( Q_{\text{sys}} \) and \( Q_{\text{leak}} \) are considered in this section, for the study and their effect in the power consumption are discussed. The variables are given with different linguistic variables.

5.5.1 Fuzzification

The considered input parameters \( P_{\text{max}} \), \( Q_{\text{sys}} \), \( Q_{\text{leak}} \) and Power are divided into five membership functions each and suitable linguistic variables are assigned to them. \( P_{\text{max}} \), \( Q_{\text{leak}} \) and Power are given linguistic variables as very low (VL), low (L), medium (M), high (H) and very high (VH). \( Q_{\text{sys}} \) is provided with linguistic variables negative big (NB), negative small (NS), average (AVG), positive small (PS) and positive big (PB). The average represents the average consumption and NS represents the minimum consumption. The PB represents the maximum consumption. The relationship between the input and output variables is shown in figure 5.8.

The existing pressure bandwidth range is equally divided into five. Minimum and maximum values of the membership function for its various degrees are fixed based on that. For example the VL value of the \( P_{\text{max}} \) is 7 bar and the range for the triangular membership function is fixed as 0.5 bar either
side. Though the leakage is measured as about 17% at present, which is not permissible and needs leakage arresting measures, it is assumed that the leakage could be controlled within 5% and that is considered as very high leakage. The details of the range of membership function for the parameters are shown in Table 5.2.

![Figure 5.8 Fuzzy inference system for inputs and output](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value of linguistic variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>P&lt;sub&gt;max&lt;/sub&gt; (bar)</td>
<td>VL</td>
</tr>
<tr>
<td>Q&lt;sub&gt;leak&lt;/sub&gt; (%)</td>
<td>1.5</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>2.1</td>
</tr>
</tbody>
</table>
For linguistic variables of consumption, the maximum and minimum quantity of air consumed is taken into account and the entire range is divided into five divisions. The range of membership function is shown in Table 5.3.

**Table 5.3 Linguistic variable values for Q\textsubscript{sys}**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value of linguistic variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q\textsubscript{sys} (SCMM)</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>0.43</td>
</tr>
</tbody>
</table>

The membership diagram for the inputs namely, operating pressure bandwidth (P\textsubscript{max}), system consumption (Q\textsubscript{sys}) and leakage consumption (Q\textsubscript{leak}) and for the output are shown from Figures 5.9 to 5.12.

**Figure 5.9 Membership function for P\textsubscript{max}**
Figure 5.10 Membership function for $Q_{sys}$

Figure 5.11 Membership function for $Q_{leak}$
5.5.2 Inference

Totally 125 \((5 \times 5 \times 5 = 125)\) rules have been formed representing all possible combinations of the membership function levels of input variables. Though the lesser number of rules with selected combination of the membership levels of variables can give results of considerable accuracy, all the possible combinations are considered here for better results.

5.5.3 Defuzzification

Like the two parameter case, the defuzzification is based on “the centre of area” method and its output is the power required to operate the compressor within the selected parameters. Defuzzification of fuzzy rules is carried out and the results are shown in Figure 5.13.

![Figure 5.12 Membership function for Power](image)
Figure 5.13 Defuzzified crisp values for given set of input values

5.5.4 Results and discussion

Figure 5.13 shows the influence of individual membership function on the results. By giving corresponding input value in the input box (e.g. [7.02 0.557 3.52]), the output is plotted accordingly. For the input \( Q_{\text{sys}} = 0.557 \text{ SCMM}, \ P_{\text{max}} = 7.02 \text{ bar} \) and \( Q_{\text{leak}} = 3.52\% \), the output plot in the rule viewer is \( \text{Power} = 3.41\text{kW} \). The thick vertical line in the input shows the position of the input in the Figure 5.13.

A three dimensional line graph of the variation of power with respect to the variation in the \( P_{\text{max}} \) value and \( Q_{\text{sys}} \) value is shown in Figure 5.14. The point A in line 1 in the graph is corresponding to the VL value of \( P_{\text{max}} \) and VL value of \( Q_{\text{sys}} \). As both the pressure and consumption are very low, the power consumed is also very low. Point B in the same line corresponds to VH value of \( P_{\text{max}} \) and VL value of \( Q_{\text{sys}} \). As the pressure is maximum, though the quantity consumed is very less, the power consumed is in the range of High. The point A in line 2 in the graph corresponds to VL.
value of $P_{\text{max}}$ and VH value of $Q_{\text{sys}}$, which leads to medium level of power consumption. Point B in the same line corresponds to VH value of both $P_{\text{max}}$ and $Q_{\text{sys}}$. This leads to VH level of power consumption.

![Figure 5.14 Variation of power with respect to variation in $P_{\text{max}}$ and $Q_{\text{sys}}$](image)

The process repeated to all the values of the input variables and the corresponding results are plotted as surface graphs as shown in Figure 5.15 and Figure 5.16. The graph in Figure 5.15 gives the combinational effect of variation in $P_{\text{max}}$ and $Q_{\text{sys}}$ on power consumed. The graph in Figure 5.16 gives the combinational effect of $Q_{\text{leak}}$ and $P_{\text{max}}$ on power consumption. The operating parameter values that will require minimum power for operation of compressor can be identified from the graphs. When the maximum pressure is VL (Very Low), system consumption ($Q_{\text{sys}}$) is NS (Negative Small) and air leakage ($Q_{\text{leak}}$) is VL (Very Low), the power consumed by the compressor is VL (Very Low), which is evident from the figures.
Figure 5.15 Effect of $P_{\text{max}}$ and $Q_{\text{sys}}$ on power consumption

Figure 5.16 Effect of $P_{\text{max}}$ and $Q_{\text{leak}}$ on power consumption
5.6 OPTIMISATION BY CONSIDERING FOUR PARAMETERS

The effect of varying three parameters in power consumption has been attempted and discussed in the earlier section. However, the usage of compressed air for miscellaneous purposes is considerable high in certain industries due to which the effect of $Q_{\text{mis}}$ in power consumption is also significant. Hence, four parameters such as maximum pressure of operating pressure bandwidth $P_{\text{max}}$, system consumption ($Q_{\text{sys}}$), miscellaneous usage ($Q_{\text{mis}}$) and percentage of leakage ($Q_{\text{leak}}$) are considered as inputs in this section. The output is the power consumed by air compressor. The Fuzzy Inference System used for this problem is shown in Figure 5.17.

![Fuzzy inference system for inputs and output](image)

Figure 5.17 Fuzzy inference system for inputs and output
5.6.1 Fuzzification

In addition to four parameters, different levels of membership function are tried for different variables during fuzzification. Two important parameters ($P_{\text{max}}$ and $Q_{\text{sys}}$) are considered with five levels of membership function. Other two parameters ($Q_{\text{leak}}$ and $Q_{\text{mis}}$) are given with three levels. The output is given with five levels of membership function. The range of membership function for the parameters $P_{\text{max}}$, $Q_{\text{sys}}$, and Power are shown in Table 5.4 and for parameters $Q_{\text{mis}}$ and $Q_{\text{leak}}$ are shown in Table 5.5.

**Table 5.4 Linguistic variable values for $P_{\text{max}}$, $Q_{\text{sys}}$ and Power**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linguistic variables and their value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{max}}$ (bar)</td>
<td>VL - 7.0</td>
</tr>
<tr>
<td>$Q_{\text{sys}}$ (SCMM)</td>
<td>NS - 0.42</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>VL - 2.2</td>
</tr>
</tbody>
</table>

**Table 5.5 Linguistic variable values for $Q_{\text{leak}}$ and $Q_{\text{mis}}$**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linguistic variables and their value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{leak}}$ (%)</td>
<td>L – 1.0</td>
</tr>
<tr>
<td>$Q_{\text{mis}}$ (%)</td>
<td>L – 0.5</td>
</tr>
</tbody>
</table>
The membership diagram for the inputs and output are shown from Figures 5.18 to 5.22. The range for each level of membership function is not kept equal for $Q_{sys}$ and Power; that helps to study the effect of any possible error in assigning values for membership functions.

![Membership function for $P_{max}$](image1)

**Figure 5.18 Membership function for $P_{max}$**

![Membership function for $Q_{sys}$ (SCMM)](image2)

**Figure 5.19 Membership function for $Q_{sys}$**
Figure 5.20 Membership function for $Q_{\text{leak}}$

Figure 5.21 Membership function for $Q_{\text{mis}}$

Figure 5.22 Membership function for output
5.6.2 Inference and Defuzzification

Totally 225 \( (5 \times 5 \times 3 \times 3 = 225) \) rules have been formed representing all possible combinations of the membership function levels of input variables. All the possible combinations are taken into consideration without minimising the combinations. Defuzzification has been carried out as explained earlier and the crisp values for different combinations can be obtained as shown in Figure 5.23.

![Defuzzification for four parameters](image)

**Figure 5.23** Defuzzification for four parameters

5.6.3 Results and discussion

The line graphs showing the variation of power with respect to \( Q_{\text{leak}} \) for the range of \( P_{\text{max}} \) values is shown in Figure 5.24. The variation of power with respect to \( Q_{\text{mis}} \) is shown in Figure 5.25. As an example, when \( Q_{\text{leak}} \) is in
the Low level, as given by point A of line 1, in Figure 5.24, the consumption is less so the power required is Very low. If the pressure increases for the same level of $Q_{\text{leak}}$, because of increased pressure, the power increases to High value (point B in line 1). When leakage increases to maximum value as in line 2, the power also increases correspondingly, because of increased total consumption. Same way, it happens to miscellaneous consumption ($Q_{\text{mis}}$) as seen from Figure 5.25. Effects of combination of these values are evaluated for all the rules and are shown as surface graphs in Figures 5.26, 5.27 and 5.28.

![Figure 5.24 Variation of power with respect to $Q_{\text{leak}}$]
Figure 5.25 Variation of power with respect to $Q_{\text{mis}}$

Figure 5.26 Effect of $P_{\text{max}}$ and $Q_{\text{sys}}$ on power consumption
Figure 5.27 Effect of $P_{\text{max}}$ and $Q_{\text{leak}}$ on power consumption

Figure 5.28 Effect of $P_{\text{max}}$ and $Q_{\text{mix}}$ on power consumption
From Figures 5.26, 5.27 and 5.28, the power required to operate the compressor for various values of the parameters can be identified and the optimum pressure range for the combination of the variables could be identified.

5.7 CONCLUDING REMARKS

The fuzzy inference system proposed is to identify the optimum values of pressure bandwidth based on system consumption and leakage. This method can be used for any specific industry with reasonable savings in energy consumption. From the simulated result, it is proved that, the reduction in operating pressure bandwidth, the reduction in the system consumption and reduction in the leakage consumption identified using fuzzy logic can minimise the power consumed by compressed air supply system. This method can be extended to other operating parameters also, depending on the nature and consumption pattern of the industry. The possibility of using various levels of membership function has also been studied. This methodology can be used during the design process of the new compressed air supply systems to identify optimum values of parameters where more uncertainty is likely to exist.

The linguistic variable and membership function taken in this study for various parameters are based on the existing range, which can be changed to different levels and tried in the future. In the case of leakage, it is assumed that there exists certain leakage and the effect of completely eliminating leakage need to be studied. The benefits of application of fuzzy based method depends on the uncertainties present in the industry in terms of variation in quantity of consumption, quantity of leakage, quantity of miscellaneous usage and the range of pressure bandwidth.
The energy conservation activities, along with this kind of optimisation techniques, need to have strategic management approach in planning and executing the energy conservation efforts. One such approach newly developed is explained in the next chapter.