CHAPTER 4

EXPERIMENTAL INVESTIGATION

4.1 INTRODUCTION

In this chapter, a brief account of the basic experimental set up, its instrumentation, arrangement of the urea injection system, after treatment of the exhaust with SCR are given. In addition the use of two different selective catalyst coated reactors arranged in series and in parallel are dealt with.

4.2 EXPERIMENTAL SETUP WITH UREA INJECTION

The Figure 4.1 shows the line diagram of the experimental setup with urea injection arrangement without introducing SCR. The major parts of the experimental setup are a single cylinder constant speed vertical water cooled Kirloskar diesel engine, an eddy current dynamometer, air intake tank, fuel measuring unit, AVL five gas analyzer, a smoke meter and post combustion exhaust gas treatment unit which consists of an urea tank, a circulating pump, a three way control valve and an urea injector.

The injection process of urea solution is shown in figure 4.1. It consists of a tank to store the urea solution, a circulating pump to pump the urea solution, a three way valve to control the flow of urea solution and a needle injector to inject urea solution in the engine exhaust. The needle injector is fitted in the exhaust pipe just nearer to the engine. By selecting the size of the needle injector and by adjusting the three way valve, the flow of urea solution could be controlled. Due to the pressure created by the pump the
urea solution is sprayed in the exhaust flue gas. No arrangements were made to study the spray pattern and the droplet size of urea injected into the exhaust gas at this point of experimental work. The three way valve was designed in such a way that it should supply the determined quantity of urea solution to the injector. The excess quantity of urea solutions is returned back to the urea tank.

**Figure 4.1 Experimental setup with urea injection arrangements**

### 4.2.1 CI Diesel Engine

The engine used in this investigation is a 5.2 kW, single cylinder, water cooled, vertical, Kirloskar, constant speed diesel engine coupled with an eddy current dynamometer. Table 4.1 shows the detailed specification of the engine and Appendix 1 shows the photographic view of the test engine.
**Table 4.1 Engine Specification**

<table>
<thead>
<tr>
<th>TYPE</th>
<th>Single Cylinder vertical water cooled 4 stroke diesel engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>81.5 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>101 mm</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>17.5 : 1</td>
</tr>
<tr>
<td>Orifice diameter</td>
<td>0.025 m</td>
</tr>
<tr>
<td>Dynamometer arm length</td>
<td>0.195 m</td>
</tr>
<tr>
<td>Power</td>
<td>5.2 kW (7HP)</td>
</tr>
<tr>
<td>Speed</td>
<td>1500 RPM</td>
</tr>
</tbody>
</table>

### 4.2.2 Loading Device

In this investigation, an eddy current dynamometer was used as a loading device. The dynamometer can be operated in two different modes. They are constant torque mode and constant speed mode. In the constant torque mode, the torque is kept constant and hence the overall power output will be proportional to the speed of the engine. In constant speed mode, the speed remains constant and, hence, the torque varies, the resultant power output too varies proportional to the torque. The specification of dynamometer is given in the Appendix 2.

### 4.2.3 Air Intake Tank

The air flow rate is measured using an air tank connected to the engine. The air intake to the engine is connected through a large rigid box with an orifice at its inlet. The tank should be large enough to damp out the pulsations in flow and be free of resonances in the normal speed range of the engine. The pressure drop across the orifice is measured by a water tube manometer. The mass flow rate of air is calculated by using the expression.
\[ M_a = C_d A_0 \sqrt{2gh_a} \rho_a \]

where \[ M_a = \text{Mass flow rate of air in kg/s} \]
\[ C_d = \text{Co-efficient of discharge of orifice (0.62)} \]
\[ A_0 = \text{Cross sectional area of the orifice} \]
\[ g = \text{Acceleration due to gravity (9.806 m/s}^2) \]
\[ h_a = \text{head of air (m)} \]
\[ h_a = \frac{h_f r_f}{r_a} \]
\[ \rho_a = \text{density of air in kg/m}^3 \]
\[ \rho_f = \text{density of manometric fluid in kg/m}^3 \]
\[ h_f = \text{liquid level difference in the manometer (m)} \]

4.2.4 Fuel Measuring Unit

The fuel consumption by the engine is measured using the conventional burette by noting the time taken to consume 10 cc of fuel was taken and using the density of the fuel, determined from a separate test, the mass of fuel used was calculated using the following equation:

\[ \text{Mass flow rate of fuel} = \frac{10 \times 3600 \times \text{density of fuel}}{T \times 10^6} \text{(in kg/h)} \]

where \[ T = \text{time taken for 10 cc fuel consumption in seconds} \]
4.2.5 AVL Five Gas Analyzer

The exhaust emission from the engine was measured using an AVL five gas analyzer (Series 4000 - for petrol and Diesel engines). The AVL five gas analyzer measures CO, CO$_2$, HC, O$_2$ and NOx from the engine exhaust. The instrument measures CO, CO$_2$ and HC using Non-dispersive infrared technology and O$_2$ and NOx by electro chemical sensor. The results are directly noted from the display. The specification and photograph of the five gas analyzer used in this investigation is given in Table 4.2 and Figure 4.2 respectively.

Table 4.2 Specification of AVL five gas analyzer

<table>
<thead>
<tr>
<th>Gas measured</th>
<th>Range</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0-10% Vol.</td>
<td>0.01% Vol.</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0-20% Vol.</td>
<td>0.1% Vol.</td>
</tr>
<tr>
<td>HC</td>
<td>0-2.000 ppm Vol.</td>
<td>1 ppm</td>
</tr>
<tr>
<td>NOx</td>
<td>0-5.000 ppm Vol.</td>
<td>1 ppm</td>
</tr>
<tr>
<td>O$_2$</td>
<td>0-25% Vol.</td>
<td>0.01 % Vol.</td>
</tr>
</tbody>
</table>

Figure 4.2 AVL 5 gas analyzer
4.2.6 Smoke Meter

In this experimental setup a hartridge smoke meter was used. It consists of two optically identical tubes, one containing clean air and the other containing the moving sample of the smoke. The clean air tube is taken as the reference. A light source and photo electric cell are mounted facing each other on a swinging arm. The movement of the change over knob alters their position from one tube to another. The photo electric cell is connected to micro ammeter with a scale calibrated from 0 to 100, indicating the light observed by the smoke in Hartridge unit. The air flows from the open end of the tube across the surfaces of the light source and the photo electric cell to provide cooling and to protect them against sooting by the smoke. The sampling probe is connected to a tapping on the exhaust pipe of a diesel engine. The smoke meter is switched on and control lever set to bring the clean air tube between light and the cell. The smoke meter dial should read zero, otherwise the meter is to be adjusted to read zero. The control lever is then moved to bring the light and cell in line with smoke tube by opening the bypass valve, the meter gives continuous and direct reading of the smoke density.

Figure 4.3 AVL Smoke Meter
4.2.7 After Treatment of Exhaust Gas Unit

Figure 4.4 shows the line diagram of after treatment of exhaust gas system. It consists of a storage tank to store the urea solution, a pump to maintain the pressure of urea solution and to circulate the urea solution to the urea nozzle injector, a nozzle injector which is fitted in the exhaust pipe nearer to the engine. A three way flow control valve is fitted in between the pump and the injector to control the flow of urea solution to the injector nozzle to inject the urea solution and a pipe line to return the excess solution back to the storage tank.

Figure 4.4 The line diagram of after treatment of exhaust gas system

4.2.7.1 SCR in the exhaust

SCR technology is designed to permit nitrogen oxide (NOx) reduction reactions to take place in an oxidizing atmosphere. It is called "selective" because it reduces levels of NOx using ammonia as a reducing agent within a catalytic system. The reducing agent reacts with NOx to convert the pollutants into nitrogen, water and tiny amounts of carbon dioxide (CO2). The reducing source is usually automotive-grade urea, otherwise
known as Diesel Exhaust Fluid, which can be rapidly hydrolyzed to produce the oxidizing ammonia in the exhaust stream. SCR technology alone can achieve NOx reduction up to 90%.

4.2.7.2 Arrangement of single SCR

The single SCR unit is fitted in the exhaust pipe line after the injection of urea solution as shown in Figure 4.5. The SCR unit consists of a bed of thin foils coated with catalyst materials. Here SCR with vanadium coated catalyst and titanium dioxide coated catalyst are used separately. The bed of these catalyst coated foils are housed in a thick metal chamber having elliptical cross section with two openings, inlet and outlet. The exhaust gas from engine enters at inlet and leaves through outlet of the SCR unit. The flow of exhaust gases over these bed of catalysts create back pressure due to obstruction in the flow. The size of the SCR bed housing is designed in such a way that it should nullify the formation of back pressure.

Figure 4.5 Single SCR with vanadium or titanium di-oxide catalyst in exhaust line
4.2.7.3 Two SCRs connected in series

Figure 4.7 shows two SCRs, i.e. the SCR with vanadium coated catalyst and the SCR with titanium di-oxide coated catalyst are connected in series in the exhaust pipe after the injection of urea solution. The exhaust gas is allowed to pass through vanadium catalyst and then through titanium di-oxide coated catalyst before it leaves to atmosphere.

Figure 4.7 Schematic of experimental setup with urea injection with introducing SCR –I and SCR -II Connected in series
Figure 4.8 Photographic view of two SCRs connected in Series

Figure 4.9 Photographic view of urea tank, circulating pump and three way control valve
4.2.7.4  Two SCRs connected in parallel

The two SCR, i.e. the SCR with titanium di-oxide catalyst and the SCR with vanadium coated catalyst are connected in parallel in the exhaust pipe line after the injection of urea solution as shown in Figure 4.10. After the injection of urea solution the mixture of NH\textsubscript{3} and the effluent of NO\textsubscript{x} are allowed to pass through two different catalysts which are connected in parallel.

![Figure 4.10 Schematic of experimental setup with urea injection along with two SCRs connected in Parallel](image)

4.3  PREPARATION OF AQUEOUS UREA SOLUTION

Many experiments involving the use of chemicals call for their use in solution form by mixing two or more substances together in known proportion. Preparing solutions accurately will improve the safety of the experimental investigation and lead to success.

The concentration of urea solution may be defined as:
Concentration of urea solution % by weight = \( \frac{\text{mass of solute}}{\text{mass of solution}} \times 100\% \)

Hence, to prepare a 10% aqueous urea solution, 10 grams of urea is dissolved in 90g of water. Like this different concentration of urea solution ranging from 10% to 50% by weight in steps of 10% was prepared.

### 4.4 PROPERTIES OF UREA SOLUTION

The Table 4.3 shows the properties of aqueous urea solution used in this experimental investigation.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg / m(^3))</td>
<td>1089</td>
</tr>
<tr>
<td>Boiling point temperature (C(^o))</td>
<td>104</td>
</tr>
<tr>
<td>Thermal conductivity [W/m.K]</td>
<td>0.57</td>
</tr>
<tr>
<td>Specific Heat (kJ / kg. K)</td>
<td>3.4</td>
</tr>
<tr>
<td>Surface Tension [N /m]</td>
<td>0.0717</td>
</tr>
<tr>
<td>Latent heat of vapourization (kJ/kg)</td>
<td>2.258</td>
</tr>
<tr>
<td>Concentration (Wt %)</td>
<td>32.5</td>
</tr>
<tr>
<td>Freezing Point (C(^o))</td>
<td>-11</td>
</tr>
<tr>
<td>pH</td>
<td>8.8</td>
</tr>
<tr>
<td>Colour</td>
<td>Colourless</td>
</tr>
<tr>
<td>Odour</td>
<td>Odourless</td>
</tr>
</tbody>
</table>

### 4.5 EXPERIMENTAL METHODOLOGY

In this research work, the experiments have been carried out in six phases on a single cylinder, four stroke, water cooled, direct injection diesel engine developing 5.2kW at 1500 rpm. Experiments were carried first, with base diesel operation without the introduction of urea solution and the SCR.
The reading required for the calculation of performance characteristics and the emission measurements were taken.

Then the experiments were repeated to get the optimized value of the flow rate and concentration of urea solution without introducing the selective catalytic reduction (SCR) technique in the engine exhaust. In the third phase of experiment, the SCR with vanadium coated catalyst was introduced in the engine exhaust. The tests were repeated for this optimized flow rate and concentration of urea solution.

In the fourth phase of experiment, the SCR with vanadium coated catalyst was replaced by the SCR with titanium di-oxide coated catalyst in the engine exhaust. The engine tests were repeated for the optimized flow rate and concentration of urea solution.

In the next phase of experiment, the SCR with vanadium coated catalyst and the SCR with titanium di-oxide coated catalyst were connected in series in the engine exhaust after treatment system. The same tests were repeated and all the emission parameters were recorded. In the last phase of experiments, both the SCR catalysts were arranged in parallel in the engine exhaust and the same tests were carried out.

4.6 THE EXPERIMENTAL PROCEDURE

Initially the engine was started and allowed to run at the rated speed for some period of time for warming up. Before the engine was loaded, the fuel flow rate, the emissions such as HC, CO, CO₂, O₂, NOx and smoke density were recorded. Then the engine was loaded gradually from 0% to 100% of full load in steps of 20%. For each and every load without introducing any urea injection and SCR technique, i.e. under base diesel operation, the fuel flow rate, the other emission parameters such as HC, CO,
CO\textsubscript{2}, O\textsubscript{2}, NO\textsubscript{x} and smoke density were recorded. Then the urea injection unit was attached in the set up as shown in figure 1 and the tests were carried out by varying the urea flow rate from 0.25 to 1.0 l/h in steps of 0.25 l/h and the optimum flow rate of urea was found.

Then tests were repeated using the optimum flow rate of urea solution by varying the concentration of urea solution from 10 to 50 % in steps of 10 % to find out the optimum concentration of urea solution for the maximum reduction of NO\textsubscript{x} was found. Then the experiments were repeated with the optimum flow rate and optimum concentration with the introduction of the Vanadium catalyst coated SCR and titanium di oxide coated SCR separately, in series and in parallel. All the parameters as mentioned in the previous paragraph were measured.

4.7 UREA REQUIRED FOR THE MAXIMUM REDUCTION OF NO\textsubscript{x}

The theoretical urea required for maximum reduction of NO\textsubscript{x} can be calculated from the mass flow rate of air and fuel as given below:

4.7.1 Calculation of Mass of Air and Fuel

The mass of air drawn and the amount fuel consumed can be calculated using

The equation given section and the values are

\[
\begin{align*}
\text{Mass of air} & = 461.32 \text{ g/min} \\
\text{Mass of fuel} & = 23.19 \text{ g/min}
\end{align*}
\]

Mass flow rate of nitrogen and oxygen can be calculated using the weight ratio of nitrogen and oxygen in air (i.e 77:23). Thus,
mass flow rate of Nitrogen = 355.216 g/min
mass flow rate of Oxygen = 106.103 g/min

4.7.2 Calculation of Number Moles

The number of moles can be calculated using the expression

\[
\text{No. of moles} = \frac{\text{Mass of the substance}}{\text{Molecular weight}}
\]

Hence, the number of moles of Nitrogen = 12.686 moles/min

The number of moles of Oxygen = 3.315 moles/min

The moles of fuel = 0.12078 mole/min

(The molecular weight of Nitrogen, Oxygen and diesel are 28, 32 and 192 respectively)

4.7.3 Calculation of Number of Moles of Reactants and Products

The number moles of reactants can be calculated using the equation of the reaction given as:

\[
\begin{align*}
\text{No of moles of reactants} &= 12.686 \text{ N}_2 + 3.315 \text{ O}_2 + 0.12708 \text{ C}_{14}\text{H}_{24} \\
&= 105.03 \text{ N}_2 + 27.44 \text{O}_2 + \text{C}_{14}\text{H}_{24} \\
&= \text{C}_{14}\text{H}_{24} + 27.44 (\text{O}_2 + 3.82 \text{ N}_2) \\
&= 1 + 27.44 (1 + 3.82) \\
&= 133.26 \text{ moles/min}
\end{align*}
\]
No of moles of products = (no of moles of reactants) \times R_{ex}

(where \( R_{ex} \) is the expansion ratio varying from 1.02 to 1.05)

Assuming an expansion ratio of 1.02, the number of moles of product is coming as 135.92 moles/min

Before the injection of urea solution the maximum NO\(_x\) recorded was 847 ppm

Estimated moles of NO\(_x\) = \frac{847}{1000000} \times 135.92

= 0.1151 moles / min

The second stage of reaction equations are (3.18) and (3.19)

4NH\(_3\) + 6NO \rightarrow 5N\(_2\) + 6H\(_2\)O

8NH\(_3\) + 6NO\(_2\) \rightarrow 7N\(_2\) + 12H\(_2\)O

The above equations are not consuming any oxygen and also their reactions are slower. Therefore, these equations are irrelevant for lean combustion, because the diesel engine always operates with excess air and the actual main two reactions given by equation (3.20) and (3.21) by which NO\(_x\) can be reduced are given below considering the presence of excess oxygen.

From the equation (3.20)

4NH\(_3\) + 4NO + O\(_2\) \rightarrow 4N\(_2\) + 6H\(_2\)O

1 mole of NO requires 1 mole of NH\(_3\)
From the equation (3.21)

\[ 4\text{NH}_3 + 2\text{NO}_2 + \text{O}_2 \rightarrow 3\text{N}_2 + 6\text{H}_2\text{O} \]

1 mole of NO\textsubscript{2} requires 2 mole of NH\textsubscript{3}

By combining the above two equations we get

1 mole of NO\textsubscript{x} requires \( \frac{3}{2} \) moles of NH\textsubscript{3}

From the first stage of reaction

\[(\text{NH}_2\text{-CO-NH}_2)+\text{H}_2\text{O} \rightarrow 2\text{NH}_3+\text{CO}_2\]

1 mole of urea produces 2 mole of NH\textsubscript{3}

By combining the two stages of reactions,

1 mole of NO\textsubscript{x} requires \( \frac{3}{4} \) mole of urea

Estimated mole of NO\textsubscript{x} = 0.1151 moles/min

Urea required for the estimated moles of NO\textsubscript{x} = 0.0863 moles/min

\[
\text{Urea required} = 0.088 \times 60 \text{ g/min} \quad (\text{molecular weight of urea} = 60)
\]

\[
= 5.18\text{g/min}
\]

\[
= 310.8\text{g/h}
\quad (4.17)
\]

The concentration of urea solution injected is 30% by weight, that means 30g of urea is dissolved in 70g of water therefore 1g of urea occupies 70/30ml of solution.

Hence, the urea flow rate = 725.2ml/h

\[
= 0.7252\text{l/h}
\]
By considering the upper limit of expansion ratio i.e. 1.05, the flow rate of urea solution with the concentration of 30% is estimated as 0.7466 l/h.

But through experimental investigation, the flow rate of 30% concentrated urea solution was optimized at 0.75 l/h and the estimated values in both the cases are well within the actual value of flow rate.

4.8 SUMMARY

This chapter dealt with a brief account of experimental setup, instrumentation used and different arrangements of SCR in the urea injection system. The two different type of catalysts used in the SCR were also discussed. The different methodologies adopted in the experimental work were also discussed. The actual quantity of urea solution required for the maximum reduction of NOx was also estimated theoretically.

4.9. CONCLUSION

In this chapter by adopting various methodologies in different experiments the flow rate of urea solution and the concentration of urea solution were optimized. Also it was justified that these optimized values are above the theoretical values. It is concluded that the higher reduction of NOx in the diesel engine emission could be possible by introducing SCR coated with two different catalysts separately and also by introducing the combination of two different SCR catalysts along with urea injection.