CHAPTER 4

EXPERIMENTAL SETUP AND PROCEDURES

4.1 INTRODUCTION

Four different biodiesels namely pongamia pinnata biodiesel, neem biodiesel, cotton seed biodiesel and jatropha biodiesel were selected and were used to develop the dual biodiesel combinations for test fuels.

The diesel fuel and raw non edible vegetable oils were purchased from nearby oil plants. The biodiesels were produced in the laboratory environment by transesterification method. The transesterification method is discussed in section 4.2.

The properties of diesel, raw biodiesels and the blends of dual biodiesels were determined and discussed in section 4.3.

The performance, emission and exergy analysis of single cylinder diesel engine were carried out with different dual biodiesels as fuel. From the experimental result analysis, optimum dual biodiesel was selected. The detailed experimental procedure was discussed in section 4.4. The experimental setup is shown in Figure 4.1 and the Table 1 shows test engine specifications. The photographic view of the engine setup is shown in Figure 4.2. The photographic view of the gas analyzer and smoke meter is as shown in Figure 4.3.
The optimum dual biodiesel performance characteristics were further increased by (i) adding additives (ii) using thermal barrier coating and (iii) preheating the dual biodiesel using a heat exchanger which utilized the waste exhaust gas. The detailed experimental procedure for the above is discussed in section 4.5. The heat exchanger enhancement is performed with circular plate inserts. The heat transfer analyses were also carried out in the heat exchanger.

![Figure 4.1 Experimental setup](image1)

![Figure 4.2 Photographic view of the engine setup](image2)
Table 4.1 Test engine specifications

<table>
<thead>
<tr>
<th>Items</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>AV1</td>
</tr>
<tr>
<td>Made</td>
<td>Kirloskar</td>
</tr>
<tr>
<td>Type</td>
<td>Single cylinder, Four stroke</td>
</tr>
<tr>
<td>Bore x Stroke</td>
<td>87.5 x 110 mm</td>
</tr>
<tr>
<td>Rated Output</td>
<td>5.2 (kW / 1500 rpm)</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>17.5 : 1</td>
</tr>
<tr>
<td>Injection Pressure</td>
<td>13.5 MPa</td>
</tr>
<tr>
<td>Injection timing</td>
<td>23° before TDC</td>
</tr>
<tr>
<td>Type of Cooling</td>
<td>Water Cooling</td>
</tr>
<tr>
<td>Loading device</td>
<td>Eddy current dynamometer</td>
</tr>
</tbody>
</table>

**Figure 4.3 Photographic view of the gas analyzer and smoke meter**

### 4.2 BIODIESEL PREPARATION

The flow chart for biodiesel preparation is shown in Figure 4.4. The biodiesel can be extracted by the following process namely pretreatment
of vegetable oil, transesterification of oils, washing and heating and biodiesel extraction.

![Flow chart for biodiesel preparation](image)

**Figure 4.4 Flow chart for biodiesel preparation**

The vegetable seeds were dried and the vegetable oil was extracted in oil mills. The vegetable oil was pretreated to remove the impurities from the extracted vegetable oil through primary filtration and secondary filtration. The primary filtration was done by mesh and then the secondary filtration was done by filter paper for removal of micro impurities. The filtered vegetable oil had small amount of moisture content which was removed by heating the oil to 110°C by an electrical heater.

The process of removal of all the glycerol and the fatty acids from the vegetable oil in the presence of a catalyst was called transesterification. The product of the transesterification of vegetable oils is called biodiesel. In this method (transesterification) triglyceride reacted with ethyl alcohol in the presence of a catalyst (NaOH) producing a mixture of fatty acids, vegetable oil ester and glycerol.

The manufacturing process of biodiesel can be carried out by either batch or continuous flow process. The maximum ester yield of 98% was possible using 20% methanol and 1% of NaOH at 60°C reaction temperature.
after 90 min. The main product of transesterification was biodiesel and the by-products produced is glycerol, which can be refined and used in cosmetic industries, and oil cake that can be used as fertilizer. The chemical reaction of the transesterification is given below;

\[
\begin{align*}
R_1\text{COOCH}_2 & \quad \text{catalyst} \quad \text{HOCH}_2 \quad R_1\text{COOCH}_3 \\
R_2\text{COOCH} + \text{Alcohol} & \quad \rightarrow \quad \text{HOCH} + R_2\text{COOCH}_3 \\
R_3\text{COOCH}_2 & \quad \text{HOCH}_2 \quad R_3\text{COOCH}_3 \\
\text{Triglyceride} & \quad \text{Glycerol} \quad \text{Biodiesel}
\end{align*}
\]

In the chemical reaction, \( R^1 \), \( R^2 \), \( R^3 \) were the long-chain hydrocarbons or fatty acid chains. Vegetable oils have palmitic, stearic, oleic, linoleic, and linolenic fatty acid chains. The triglyceride was converted stepwise into diglyceride, mono glyceride and finally into glycerol.

The esterified vegetable oil was then transferred to a separating funnel and left for 8 hours settling period. The glycerol formed in the separating funnel was removed and the vegetable oil ester (biodiesel) was collected from the funnel.

The vegetable oil ester was then washed by distilled water to remove the impurities. Distilled water was added to the separating funnel and this water settled all the impurities at the bottom of the funnel. Next, the water with impurities was then removed and then, the vegetable oil ester was collected from funnel and further heated to 110°C to remove the water poured during washing. Thus after finishing the water washing and heating, pure biodiesel was extracted.
4.3 PHYSICAL AND CHEMICAL PROPERTIES

The biodiesel properties like calorific value, kinematic viscosity, density, flash point temperature, cetane number, surface tension and corrosion test for the test fuels (DPN 1, DPN 2, DPN 3, DPN 4, DPN 5, DPN 6, DPC 1, DPC 2, DPC 3, DPC 4, DPC 5, DPC 6, DPJ 1, DPJ 2, DPJ 3, DPJ 4, DPJ 5, DPJ 6, DCJ 1, DCJ 2, DCJ 3, DCJ 4, DCJ 5, DCJ 6, DNJ 1, DNJ 2, DNJ 3, DNJ 4, DNJ 5, DNJ 6, DNC 1, DNC 2, DNC 3, DNC 4, DNC 5 and DNC 6), raw vegetable oils, biodiesels and sole diesel were investigated. The property values are discussed in Chapter 6.

4.3.1 Calorific Value

The calorific values of raw oils, biodiesel and dual biodiesel were determined in the laboratory by bomb calorimeter. The calorimeter has a cylindrical bomb in which combustion occurs. The bomb has two valves at the top. One supplies oxygen to the bomb and the other releases the exhaust gases. A crucible in which a quantity of fuel sample to be burnt was arranged between the two electrodes. The calorimeter was fitted with water jacket which surrounds the bomb.

Fuel sample was placed into the crucible. A fuse wire (whose weight is known) was stretched between the electrodes and the close contact with the test fuel. Pure oxygen was supplied to the bomb through the valve. The bomb was then placed in the calorimeter. The thermometer indicates a steady temperature after the fuel was fired and temperature readings were recorded in 30 second intervals until the maximum temperature was attained. The constant temperature from the reading was taken for the calorific value calculations.

Heat of combustion of the fuels, \( H = \frac{WT}{M} \), calories per gram
where,  

$W = \text{Energy equivalent of calorimeter in calories per } ^\circ\text{C.}$

$T = \text{Temperature rise in } ^\circ\text{C.}$

$M = \text{mass of the blend fuel samples in grams.}$

$H = \text{heat of combustion of the fuels in calories per gram.}$

### 4.3.2 Kinematic Viscosity

Viscosity is the internal resistance offered by the fluid to the movement of one layer of fluid over an adjacent layer. It is due to the cohesion between the molecules of the fluid. The kinematic viscosity of the raw oil, biodiesel, and dual biodiesel is determined using Redwood Viscometer.

The orifice with ball valve in the redwood viscometer was closed and then, the test fuel was filled in the cylindrical oil cup up to the mark in the cup. Required amount of water was filled in the water bath. The water was heated to a particular temperature. The water was stirred and the uniform temperature was maintained. At a particular temperature, the ball was lifted and the oil was collected in the 50 ml flask and the time taken in seconds for the collection 50 ml of oil was noted. A stop watch was used to measure the time taken.

\[
\text{Kinematic viscosity} = At + B/t \text{ in Centistokes}
\]

where, $t$ is time taken for collection of 50 ml of oil in sec

A and B are constants. Here $A = 0.26$ and $B = 171.5$. 
4.3.3 Density

Density is a basic physical property of a homogeneous substance. Initially a dry 25 mL graduated cylinder was weighed using a digital weight balance. Then it was removed from the weight balance and 10 mL of test fuel was added in the cylinder. Again the graduated cylinder containing test fuel was weighed. The weight of oil was recorded and then the density of the test fuel was calculated using the formula (Density = mass / Volume).

4.3.4 Flash Point Temperature

Flash point temperature of raw oils, biodiesel and dual biodiesel is determined using Pensky Marten’s apparatus. Flash point temperature is the lowest temperature at which the lubricating oil gives off enough vapors that ignite for a moment when tiny flame is brought near it (Ganesan 2003). Flash point temperature is used to indicate the fire hazard of fuel and evaporation losses under high temperature.

The test fuel was filled in a cup up to the mark. The lid on the top was fixed through which a thermometer and a stirrer are inserted. The fuel was heated by 5°C per minute. The stirrer is continuously rotated. At every 1°C rise of temperature, a test flame was introduced into the oil vapor. When a test flame causes a distinct flame in interior cup, the temperature is observed and recorded which represents the flash point temperature.

4.3.5 Cetane Number

The cetane number is the most important fuel property of compression ignition engines which affects the engine performance and exhaust emissions.
The formula for calculating the cetane number is \( = (0.72 \times \text{diesel index}) + 10 \)

where Diesel index = \((\text{Aniline point (°F) x API gravity at 60°F})/100\)

Aniline point is the lowest temperature at which the oil is completely miscible with an equal volume of aniline.

API (American Petroleum Institute) gravity is given by

\[
\text{API} = \frac{141.5}{\text{Specific gravity at 60°F}} - 131.5
\]

4.3.6 Surface Tension

The surface tension of the test fuels is determined by drop counting method in a stalagmometer. The stalagmometer is a glass tube which is widened in middle part. The test fuel was filled inside the stalagmometer and the fuel flowed out from the bottom side of the stalagmometer and formed the drop due to the smaller diameter of the bottom side. The fuel drops were counted and collected in the bottle. Similarly, water was filled inside the stalagmometer and the water drops were counted.

Surface tension = \((\text{surface tension of water} \times \text{density of fuel} \times \text{number of water drops}) / (\text{density of water} \times \text{number of fuel drops})\).

4.3.7 Corrosion Test

The copper corrosion test measures the corrosion tendency of the fuel when used with copper, brass, or bronze parts. Corrosion is a chemical action that destroys the surface of a metal by oxidation alone or in combination with a chemical process. It should be tested in fuels, especially for transportation and storage conditions.
In the present study corrosion level is measured according to the ISO -2160 standard test method. In this method, a polished copper strip was immersed in a specific volume of the sample test fuel and heated at 50°C for 3 hours. At the end of the heating period, the strip was removed, washed and the colour assessed against corrosion standards. The copper strip colour indicates the test fuel classification according to ISO -2160.

4.4 ENGINE PERFORMANCE CHARACTERISTICS

Engine performance is an indication of the degree of success. The performance of the dual biodiesel blends was evaluated with diesel. The diesel engine was operated with different dual biodiesel combinations.

The performances of test fuels were analyzed in a Kirloskar make single cylinder, four-stroke, direct injection diesel engine coupled with an eddy current loading device. Experiments were conducted with varying loads while the engine speed was kept constant at the rated speed of 1500 rpm. Tests were conducted at 0, 20, 40, 60, 80 and 100% of the rated load for all the fuels. Three experiments for each load were carried out for test repeatability.

Fuel flow rates were obtained with calibrated burette. The exhaust gas temperatures were measured using Chromel Alumel (K-Type) thermocouple. The parameters like brake specific fuel consumption, brake thermal efficiency and brake specific energy consumption were evaluated for different load conditions.

Before the engine was switched off, it was run by diesel fuel in order to flush out the vegetable oil from the fuel line and fuel filter. By doing this, cold starting problems of the engine could be avoided to a large extent.
Flow control valves, fuel measurement devices and thermocouples were provided at different places to make operation possible.

The engine analyses were conducted to find out its performance, emission values and exergy parameters in the diesel engine using dual biodiesels. The emission analysis is discussed in section 4.4.1 and the exergy analysis is discussed in section 4.4.2.

4.4.1 Emission Characteristics

The emission characteristics of the dual biodiesel blends are measured using smoke meter and exhaust gas analyzer at the engine steady state condition. The AVL make smoke meter was utilized to find the smoke opacity of the exhaust gas. The smoke meter is measured the smoke opacity by light obscuration method. In this method, the intensity of a light beam is reduced by smoke, which is a measure of smoke intensity. The Crypton make exhaust analyzer was used to measure the carbon monoxide (CO), carbon dioxide (CO$_2$), hydrocarbon emission (HC) and nitrogen oxides (NOx). The exhaust gas analyzer is measured the NOx emissions by chemical cell method. Moreover, the exhaust gas analyzer is measured the carbon monoxide, carbon dioxide emissions and hydrocarbons by Non dispersive infra red method (NDIR).

4.4.2 Exergy Analysis

Exergy is nothing but the amount of work got when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings (Aghbashlo et al 2013). This takes place because of reversible process, involving interaction only with this component of nature.
The exergy analysis is done to recognize the points where the destruction of exergy exists. This destruction of exergy is a normal function of the irreversibility of the process or degradation of the quality of energy resources.

The rate of fuel consumption, engine cooling water inlet and outlet temperatures, exit temperature of exhaust gas, flow rate of engine cooling water, water temperature in the calorimeter, exhaust gas temperature in the calorimeter, mass flow rate of water through calorimeter, exhaust gas pressure manometer readings were observed and recorded. Then, the exergy analysis was carried out theoretically using analytical expressions.

4.5 ENHANCEMENT OF PERFORMANCE CHARACTERISTICS

The optimum dual biodiesel is found from the performance and emission analysis. The performance characteristics of optimum dual biodiesel are improved by: (i) using additives with dual biodiesel, (ii) using thermal barrier coated engine and (iii) preheating the fuel by recovering waste heat from a heat exchanger. From the above three ways, one of the effective ways is selected and suggested for performance enhancement.

4.5.1 Additives

Three different additives namely, ethanol, diethyl ether and 2-methoxy ethyl acetate (MEA) were selected from the literatures for improving the optimum dual biodiesel. Ethanol (E) and diethyl ether (DEE) had high Cetane number and oxygen content.

Ethanol, DEE and MEA are the additives which were blended with the optimum DPN blends separately. Therefore, this chapter is devoted to utilize i) DPN with ethanol, ii) DPN with DEE and iii) DPN with MEA in CI
engines and the effects of these fuels on performance characteristics are investigated.

DPN 1, DPN 2, DPN 3 and DPN 4 are the optimum blends. An additive of 15% vol was added to the above blends. Therefore, DPN 1+E, DPN 2+E, DPN 3+E, DPN 4+E, DPN 1+DEE, DPN 2+DEE, DPN 3+DEE, DPN 4+DEE, DPN 1+MEA, DPN 2+MEA, DPN 3+MEA and DPN 4+MEA were prepared for the engine performance test. The performance analysis and emission analysis were examined with the above additive mixed test fuels.

4.5.2 Thermal Barrier Coating

The performance and the emission characteristics of both the baseline diesel engine and LHR engine with dual biodiesel were analyzed and compared. The experiments were conducted on a stationary single cylinder, four-stroke diesel engine with and without the ceramic material of Al_{2}O_{3} - TiO_{2} (Aluminium Oxide-Titanium dioxide) coating in the piston crown and cylinder head. The ceramic coating was performed by plasma spray method. The photos of the coated piston and cylinder head are shown in Figure 4.5, Figure 4.6 and Figure 4.7.

Tests were conducted at 0, 25, 50, 75, and 100% of the rated load for all the fuels with and without coated engines. The coated engine was operated on diesel first and then on optimum dual biodiesel and their blends. The performance and the emission characteristics of the dual biodiesel blends were compared with those of the baseline engine and LHR engine.
Figure 4.5 $\text{Al}_2\text{O}_3$ - TiO$_2$ coated diesel engine piston

Figure 4.6 $\text{Al}_2\text{O}_3$ - TiO$_2$ Coated cylinder head

Figure 4.7 $\text{Al}_2\text{O}_3$ - TiO$_2$ coated piston and cylinder head
4.5.3 Waste Heat Recovery

The waste heat from the exhaust gas of the diesel engine was recovered by a counter flow double pipe heat exchanger. The heat exchanger was coupled with the exhaust pipe of the diesel engine. The heat exchanger has three outer tubes and three inner tubes. The outer tubes are made up of cast iron and they had 38.1 mm diameter and 500 mm length. The inner tubes were made up of copper and they had 19.05 mm diameter and 600 mm length.

The outer tube carried the exhaust gas from the diesel engine and the inner tube carries the dual biodiesel. An oil pump was connected between the inner tube and dual biodiesel tank and it was used to circulate the dual biodiesel from the tank to the heat exchanger and the heat exchanger to the tank. The dual biodiesel absorbed the heat from the exhaust gas by convection heat transfer.

Thermocouples and U tube manometer were located in the heat exchanger pipes to measure the temperature and pressure drop of the exhaust gas. The exhaust gas velocity was measured by the anemometer. A digital thermometer was fitted with the dual biodiesel tank to monitor the temperature of the fuel.

The dual biodiesel temperature was maintained at 60°C by using the exhaust gas bypass valve arrangement in the heat exchanger. Next, the preheated dual biodiesel was supplied to the diesel engine as the fuel. By preheating the dual biodiesel, the viscosity of the dual biodiesel was further reduced. Then the performance and emission characteristics of the preheated dual biodiesel were performed and analyzed.
Figure 4.8 Overall test engine setup

Figure 4.9 Double pipe heat exchanger with inserts

Figure 4.10 Photographic view of double pipe heat exchanger
4.5.3.1 Augmentation of heat exchanger performance

Inserts are generally utilized for the heat transfer augmentation in flow through double pipe heat exchangers. In this present study, the circular plate inserts with four U-shaped outer cuttings were used to enhance the turbulent flow and to increase the heat transfer effectiveness. The circular plate insert is shown in Figure 4.11.

The circular plate inserts were arranged in a copper strip with definite pitch ratios and fitted inside the inner tubes of the heat exchanger. The circular plate type inserts fitted with copper strip are shown in Figure 4.12. The dual biodiesel was allowed to flow inside the inner tube of the heat exchanger for five different mass flow rates. The temperatures, pressures and time taken for the flow were observed and recorded. From the observation readings, the Reynolds number, Nusselt number, friction factor and effectiveness of the heat exchanger were investigated and compared with those of the plain tube.

![Figure 4.11 Circular type insert with U-shape grooved](image1)

![Figure 4.12 Circular plate type inserts fitted in the copper tube](image2)
4.6 GOVERNING EQUATIONS

The engine performance calculations for diesel and dual biodiesel blends are calculated by the formulae given in section 4.6.1, the exergy analysis formulae are given in section 4.6.2 and the theoretical expressions for the heat exchanger are given in section 4.6.3.

4.6.1 Analytical expressions for performance analysis

The analytical expressions for specific fuel consumption, total fuel consumption, mass flow rate, fuel power, brake power, torque, brake thermal efficiency and brake specific energy consumption are given below:

Specific fuel consumption is the ratio of the total fuel consumption to the brake power of the engine.

\[
\text{Total fuel consumption (TFC)} = \frac{10}{t} \times \frac{3600}{1000} \times \text{Specific gravity of fuel, } \text{kg/h}
\]  
(4.1)

where \( t = 10 \text{ cc fuel consumption time in seconds} \)

Specific fuel consumption = \( \frac{TFC}{BP} \), \( \text{kg/kWh} \)  
(4.2)

Mass flow rate, \( m_f = \frac{TFC}{3600} \), \( \text{kg/s} \)  
(4.3)

Fuel Power, \( Q_f = m_f \times \text{Calorific value of fuel, } \text{kW} \)  
(4.4)

Brake Power (BP) = \( \frac{2 \pi NT}{60} \), \( \text{kW} \)  
(4.5)

where, Torque (T) = \( W \times r_{\text{eff}} \), \( \text{N-m} \)  
(4.6)

\( W = \text{net load applied, N} \)
\[ r_{\text{eff}} = \text{Brake drum radius} + \text{rope radius} \text{ (m)} \]

\[ N = \text{rated engine speed, rpm} \]

Brake thermal efficiency is the ratio of energy in the brake power to the input fuel energy.

\[
\text{Brake thermal efficiency} = \frac{\text{BP}}{\text{FP}}, \% 
\]

(4.7)

Brake specific energy consumption = SFC\times\text{Calorific value}, \text{kJ/kWh}

(4.8)

4.6.2 Analytical expressions for exergy analysis

The exergy analyses were carried out by the following expressions described by Debnath et al (2013).

Fuel energy was calculated by inserting the value of mass flow rate and lower heating value in Equation (5.9).

Fuel energy supplied per unit time, \( Q_{\text{in}} = m_f \times \text{LHV} \), kW

(4.9)

Torque and speed of the engine were substituted in Equation (4.10) and the shaft power of the engine was calculated.

\[
\text{Shaft power} = \text{Brake power of the engine, } Q_s = \frac{2\pi NT}{60}, \text{kW} 
\]

(4.10)

Energy in cooling water per unit time, \( Q_w = m_w \times C_{pw} \times (T_{wo} - T_{wi}) \), kW

(4.11)

where, \( C_{pw} = \text{Specific heat capacity of water, kJ/kgK} \).
Energy in exhaust gas per unit time, $Q_e = m_e \times C_{p_e} \times (T_{ei} - T_{amb})$, kW \hspace{1cm} (4.12)

where, $C_{p_e}$ = Specific heat capacity of exhaust gas, kJ/kgK.

Unaccounted energy losses per unit time $Q_u = Q_{in} - (Q_s + Q_w + Q_e)$, kW \hspace{1cm} (4.13)

In a diesel engine the availability of the fuel ($A_{in}$) is converted into shaft availability ($A_s$), cooling water availability ($A_w$), exhaust gas availability ($A_e$) and destructed availability ($A_d$). These forms of exergies are calculated according to the following analytical expressions:

Inserting the values for the mass flow rate, lower heating value, and mass fractions Equation (4.14) resulted in the input availability of the fuel.

$$A_{in} = [m_f \times LHV \times \{1.0401 + 0.1728 (\frac{H}{C}) + 0.0432 (\frac{O}{C}) + 0.2169 (\frac{S}{C})[1 - 2.0628 (\frac{H}{C})])\}, kW \hspace{1cm}(4.14)$$

Shaft availability, $A_s$ is a measure of the brake power of the engine. It is calculated by using Equation (4.10).

Cooling water availability ($A_w$) was calculated by inserting the values of cooling water energy, specific heat value and measured temperature values in Equation (4.15).

$$A_w = Q_w - [m_{we} \times C_{pw} \times T_{amb} \times \ln(\frac{T_{wo}}{T_{wi}})], kW \hspace{1cm} (4.15)$$

Similarly exhaust gas availability ($A_e$) was found out by means of Equation (4.16).
\[ A_e = Q_e + (m_f + m_a) \times T_{amb} \times \left\{ \frac{C_{pe}}{T_{ei}} \ln \left( \frac{T_{amb}}{T_{ei}} \right) - R_e \times \ln \left( \frac{P_{amb}}{P_{ei}} \right) \right\}, \text{kW} \]

Where \( R_e \) = Molecular weight, kJ/kgK.

Destructed availability \((A_d)\) is calculated by substituting the values of \( A_{in}, A_s, A_w \) and \( A_e \) in Equation (4.17).

\[ A_d = A_{in} - (A_s + A_w + A_e), \text{kW} \]  (4.17)

Exergy efficiency \((\eta_{ex})\) is found out by means of,

\[ \eta_{ex} = 1 - \left( \frac{A_d}{A_{in}} \right), \% \]  (4.18)

### 4.6.3 Analytical expressions for heat exchanger

The analytical expressions of heat transfer, average heat transfer rate, Nusselt number, Reynolds number, friction factor and effectiveness for fluids flow in a double pipe heat exchanger is given below:

Heat transferred from the exhaust gas, \( Q_h = m_h C_{ph}(T_{h1} - T_{h2}) \) (4.19)

where, \( m_h \) - mass flow rate of exhaust gas, kg/s.

\( C_{ph} \) - specific heat of exhaust gas, J/kgK

\( T_{h1} \) - Entry temperature of exhaust gas

\( T_{h2} \) - Exit temperature of exhaust gas

Heat transferred to the dual biodiesel, \( Q_c = m_c C_{pc}(T_{c2} - T_{c1}) \) (4.20)

where, \( m_c \) - mass flow rate of dual biodiesel, kg/s.

\( C_{pc} \) - specific heat of dual biodiesel, J/kgK
\( T_{c1} \) - entry temperature of dual biodiesel

\( T_{c2} \) - exit temperature of dual biodiesel

The average heat transfer rate is calculated by,

\[
Q_{\text{avg}} = \frac{Q_h + Q_c}{2} \quad (4.21)
\]

The overall heat transfer coefficient \( U \) can be analyzed from,

\[
Q_{\text{avg}} = UA \Delta T_{\text{lm}} \quad (4.22)
\]

where,

\( A \) - heat transfer surface area, \( m^2 \)

\( U \) - Overall heat transfer coefficient, \( W/m^2K \)

\( \Delta T_{\text{lm}} \) - Logarithmic mean temperature difference

The Nusselt number was calculated by using the formulae in Equation (5.23).

\[
\text{Nusselt number, } Nu = \frac{hd}{k} \quad (4.23)
\]

where, \( h \) – heat transfer coefficient, \( W/m^2K \)

\( d \) - diameter of the pipe, \( m \)

\( k \) - thermal conductivity, \( W/mK \)

The Reynolds is determined by,

\[
\text{Reynolds number, } Re = \frac{\rho Vd}{\mu} \quad (4.24)
\]
where,

\( \rho \) - density of fuel, kg/m\(^3\)

\( V \) - Velocity of flow, m/s

\( \mu \) - dynamic viscosity of fuel, Ns/m\(^2\)

The friction factor was found out by,

\[
\text{Friction factor, } f = \frac{\Delta P}{\left( \frac{1}{2} \right) \left( \frac{\rho V^2}{d} \right)}
\]  \hspace{1cm} (4.25)

where \( \Delta P \) - pressure drop, Pa

The effectiveness is calculated by,

\[
\text{Effectiveness, } \varepsilon = \frac{1 - \exp[-N(1 - C)]}{1 - C \exp[-N(1 - C)]}
\]  \hspace{1cm} (4.26)

where, \( N = \text{NTU} = \frac{UA}{C_{\text{min}}} \) \hspace{1cm} (4.27)