CHAPTER 4

INFLUENCE OF FLOW CONTROL AND COOLING ON
SUBMERSIBLE INDUCTION MOTOR

4.1 INTRODUCTION

Power consumption per hectare for any crop depends on the factors, namely, horse-power-rating of the pump-set, water level of the well or the tube-well, capacity of the pump, size of the delivery pipes, condition of the water extraction machineries, distance between the place of the water-source and the field to be irrigated, quality of the soil, terrain condition, and the water-resource etc. These factors vary considerably across regions. Higher horse-power pump-sets lift more water from the well than the lower horse-power pump-sets. The water outlet of the pump-set is directly used for irrigation, if the water availability is more, and this is called Flood Method Irrigation (FMI). To increase the irrigation efficiency, now-a-days, the Drip Method of Irrigation (DMI) is employed. The consumption of water by the crops under DMI is significantly less compared to that of FMI. Since the water is supplied through a pipe-network in DMI, mainly using groundwater, the water supply can be controlled easily. The pattern of water usage under DMI is expected to be different with those of FMI. It is a known fact that due to rapid energisation of the pump-set sand the cultivation of water-intensive-crops that is widespread, the consumption of electricity by the agricultural sector has increased manifold since independence. Though the increased consumption of electricity indicates better growth of the agriculture, many researchers have reported that the electricity is not used efficiently in the
agriculture sector due to various reasons. One among the options available for increasing the efficiency of electricity usage in agriculture is DMI. A few preliminary level studies on DMI have shown that the micro-irrigation technology is not only useful for reducing the consumption of water, but also useful in energy saving. DMI is efficient, if water-resource is good and capable of supplying continuously. During the last forty years, India has been witnessing a decline in gravity-flow-irrigation, and consequently, millions of small private tube-wells have been put to use.

Further, enhanced use of groundwater has led to wells being bored increasingly deeper, and farmers requiring higher-capacity pumps to lift water. This extraction has not only increased the cost to the farmers and the utilities, but progressively worsened the water availability in various regions.

Table 4.1 Availability of Ground-water in India

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Name of the State</th>
<th>Total No. of Assessed Units</th>
<th>Safe</th>
<th>Semi-critical</th>
<th>Critical</th>
<th>Over-exploited</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>No. of units</td>
<td>%</td>
<td>No. of units</td>
<td>%</td>
</tr>
<tr>
<td>1</td>
<td>Andhra Pradesh</td>
<td>1231</td>
<td>760</td>
<td>62</td>
<td>175</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>Gujarat</td>
<td>209</td>
<td>97</td>
<td>46</td>
<td>69</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>Haryana</td>
<td>113</td>
<td>42</td>
<td>37</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Karnataka</td>
<td>175</td>
<td>93</td>
<td>53</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>Kerala</td>
<td>151</td>
<td>101</td>
<td>67</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>Madhya Pradesh</td>
<td>312</td>
<td>264</td>
<td>84</td>
<td>19</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>Maharashtra</td>
<td>318</td>
<td>287</td>
<td>91</td>
<td>23</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>Punjab</td>
<td>137</td>
<td>25</td>
<td>18</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>Rajasthan</td>
<td>236</td>
<td>32</td>
<td>14</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>Tamil Nadu</td>
<td>377</td>
<td>145</td>
<td>38</td>
<td>57</td>
<td>15</td>
</tr>
<tr>
<td>11</td>
<td>Uttar Pradesh</td>
<td>803</td>
<td>665</td>
<td>83</td>
<td>88</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>Uttarakhand</td>
<td>17</td>
<td>12</td>
<td>70</td>
<td>3</td>
<td>18</td>
</tr>
</tbody>
</table>

Source: Dynamic ground water-resources of India
The State-wise availability of Ground-water-resource is shown in Table 4.1. Of the 5723 Administrative units (blocks/mandals, taluks, and districts) in the country assessed by the Central Ground Water Board, (Kirit et al 2007 and Antonette D’Sa 2010), ground-water-resources were found semi-critical in 550 blocks, critical in 226 blocks, and over-exploited in 839 blocks; because their annual groundwater draft exceeded long-term-rate of annual recharge. Threatened blocks include semi-critical, critical, and over-exploited; at present, seven states (Andhra Pradesh, Tamil Nadu, Rajasthan, Punjab, Gujarat, Karnataka, and Haryana) in peninsular and western India account for 80% of these. Simultaneously, ground-water-stressed areas also have a high concentration of irrigation wells, with the majority in the peninsular region being fitted with electric pumps, as shown in Table 4.2.

Over-exploitation leads to:

i) Increase in pumping-depths, reduction in well/tube-well yields, and rise in the cost of pumping ground water.

ii) Widespread and acute scarcity of ground water in summer months for irrigation and drinking purposes. Farmers have been forced to deepen their wells and install high-powered pumps. Rich farmers may cope with this challenge relatively easily; but small and marginal farmers, many of whose wells are supported by shallow aquifers, often find it difficult.
Table 4.2 Irrigation Wells in the Peninsular Region

<table>
<thead>
<tr>
<th>Name of the State</th>
<th>Number of Irrigation-Wells</th>
<th>Wells with Electrical Pumps</th>
<th>Number of critical and over-exploited blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andhra Pradesh</td>
<td>1929057</td>
<td>1691502</td>
<td>296</td>
</tr>
<tr>
<td>Gujarat</td>
<td>1082977</td>
<td>568117</td>
<td>43</td>
</tr>
<tr>
<td>Karnataka</td>
<td>860363</td>
<td>807377</td>
<td>68</td>
</tr>
<tr>
<td>Rajasthan</td>
<td>1341118</td>
<td>510020</td>
<td>190</td>
</tr>
<tr>
<td>Tamilnadu</td>
<td>1891761</td>
<td>1412697</td>
<td>175</td>
</tr>
<tr>
<td>Rest of India</td>
<td>18503268</td>
<td>9943486</td>
<td>1065</td>
</tr>
</tbody>
</table>

4.2 EFFECT OF DISCHARGE ON POWER CONSUMPTION

The efficiency of the agricultural submersible-pump-set is in the range of 45% to 55% during its maximum discharge. This is possible only with very few bore-wells which have very good water-resources. From Table 4.1, it is clear that, in many places, the bore-wells are being operated with poor water-resources and this leads to low water discharge mode of pumps; this again is the cause for the poor efficiency and hence, the power loss. By avoiding such low discharge mode of operation in water pumping, energy could be conserved.

The water discharge of the pump from the bore-well at the time of starting is more due to stagnant water. As the time passes, the water discharge from the pump gets reduced due to the poor water-resource. In such circumstances, the pumps are operated continuously with less discharge, and the tank or the mud-reservoir is employed to store the water. After storage, the water is used to irrigate the field. The performance report of 7.5-HP submersible pump-set is shown in Table 4.3.
Table 4.3 Performance Report of 7.5-HP Submersible-pump-set

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Discharge (lpm)</th>
<th>Current (A)</th>
<th>Input Power (kW)</th>
<th>Pump output (kW)</th>
<th>Overall efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>331</td>
<td>13.94</td>
<td>6.12</td>
<td>0.12</td>
<td>1.95</td>
</tr>
<tr>
<td>2</td>
<td>308</td>
<td>14.27</td>
<td>6.37</td>
<td>1.12</td>
<td>17.65</td>
</tr>
<tr>
<td>3</td>
<td>282</td>
<td>14.57</td>
<td>6.61</td>
<td>1.96</td>
<td>29.61</td>
</tr>
<tr>
<td>4</td>
<td>257</td>
<td>14.79</td>
<td>6.78</td>
<td>2.64</td>
<td>38.85</td>
</tr>
<tr>
<td>5</td>
<td>226</td>
<td>14.96</td>
<td>6.90</td>
<td>3.06</td>
<td>44.40</td>
</tr>
<tr>
<td>6</td>
<td>189</td>
<td>14.89</td>
<td>6.89</td>
<td>3.20</td>
<td>46.48</td>
</tr>
<tr>
<td>7</td>
<td>147</td>
<td>14.49</td>
<td>6.60</td>
<td>2.98</td>
<td>45.17</td>
</tr>
<tr>
<td>8</td>
<td>118</td>
<td>13.86</td>
<td>6.16</td>
<td>2.58</td>
<td>41.94</td>
</tr>
<tr>
<td>9</td>
<td>97</td>
<td>12.92</td>
<td>6.08</td>
<td>2.12</td>
<td>34.86</td>
</tr>
</tbody>
</table>

From Table 4.3, following inferences could be made:

- The efficiency is maximum at the discharge of 189 lpm. The operating point of the pump that is declared by the manufacturer depends on the head to be pumped.
- The input power consumed by the motor at the discharge of 189 lpm is 6.89 kW; but for the discharge of 97 lpm, the motor consumes a power of 6.08 kW. Comparatively, more power is consumed for low water-discharge.
- If the motor is operated at the declared point, less amount of energy will be sufficient to pump the same quantity of water.
- Reduced discharge of water provides less convection of heat inside the bore-well, resulting in poor cooling of submersible motor.
4.3 IMPLEMENTATION OF ELECTRONIC CONTROL IN IRRIGATION

The flow-based / discharge-based automatic ON / OFF control of submersible motor is used to conserve energy in critical and over-exploited water-resource areas. Irrigation control has been incorporated in motor starter with Flow sensor, Moisture sensors, and Solenoid valves so as to improve the utilization of water and power consumption in the agriculture sector. The block diagram of automated irrigation and water pumping system is shown in Figure 4.1. The proximity type flow sensor is used to sense the discharge-flow-rate; the water level sensors are used in the tank or mud-reservoir to sense the water storage level. Discharge, water level, and moisture conditions are monitored by the controller. The submersible pump is controlled by the controller using power-driver circuit. The solenoid valves have been employed to control the field irrigation system.

Figure 4.1 Block Diagram of Automated Pumping and Irrigation System
The basic operation of the controller is described in Figure 4.2 to Figure 4.5.

Figure 4.2 Flowchart for Controller Initialization and Function

Figure 4.3 Flowchart for Sensing of Parameters
Figure 4.4 Flowchart for Controller operation
Figure 4.5 Flowchart for Sub-functions C and D

where 'S' – Main Solenoid valve
'S1' – Solenoid valve for Field -1 (F1)
'S2' – Solenoid valve for Field -2 (F2)
The different subsystems of the electronic irrigation control system are:

- Flow sensor
- Moisture sensor
- Solenoid valve
- Control circuit

The Flow-meter PDLC4020, shown in Figure 4.6, manufactured by Frehnig Instruments and Controls, Coimbatore, is used as a flow sensor. The paddle wheel sensor is attached with the flow sensor, rotating on a long-life-bearing and shaft. The sensor has three types of configuration, namely, flanged-end-configuration, screwed-end-configuration, and OEM weldable fittings. In all the three configurations, the sensor is of insertion type, enabling ease of inspection and maintenance.

![Figure 4.6 PDLC4020 Flow-meter](image)

The specifications of the flow sensor are:

Accuracy: +/- 2.0%, Repeatability: +/- 1.0%,

Flow range: 0.3 m/sec to 7 m/sec, Pipe size: 19 mm to 300 mm.
Wheatstone bridge is used as the moisture sensing circuit. The resistance of the soil is directly proportional to the soil moisture content. The electrode is used to measure the moisture content and it is connected to the Wheatstone bridge.

A solenoid valve is used for routing the water to the field to be irrigated. This valve is actuated by a 12 V electro-magnetic coil as shown in Figure 4.7.

![Solenoid Valve](image)

**Figure 4.7 Solenoid Valve**

The schematic diagrams of the Power and Control Circuit are shown in Figure 4.8 and Figure 4.9, respectively.

![Power Circuit Schematic](image)

**Figure 4.8 Power Circuit: Schematic**
The PCB Layout Diagram for the Control Circuit is shown in Figure 4.10 and Figure 4.11 shows the corresponding 3-D View.

Figure 4.10  Control circuit: PCB Layout

Figure 4.11 Control circuit: 3-D View
The PCB Layout Diagram for the Power Circuit is shown in Figure 4.12 and Figure 4.13 shows the corresponding 3-D View.

Figure 4.12  Power circuit: PCB Layout

Figure 4.13  Power circuit: 3-D View
4.4 TEST RESULTS

The Electronic Flow Control mechanism was fixed with a 7.5-HP, 20-stage Submersible pump-set in an agriculture field at Siruvalur village, Gopichetipalayam Taluk. The performance of the Submersible pump-set without flow control mechanism is given in Table 4.4.

Table 4.4 Performance of Pump without Flow Control

<table>
<thead>
<tr>
<th>Time of operation</th>
<th>Duration (h)</th>
<th>Status of the Pump</th>
<th>Discharge (lps)</th>
<th>Quantity of water Pumped (kL)</th>
<th>Energy Consumed (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.00 - 6.30</td>
<td>0.50</td>
<td>ON</td>
<td>4.50</td>
<td>8.10</td>
<td>3.32</td>
</tr>
<tr>
<td>6.30 - 7.00</td>
<td>0.50</td>
<td>ON</td>
<td>4.20</td>
<td>7.56</td>
<td>3.29</td>
</tr>
<tr>
<td>7.00 - 8.00</td>
<td>1.00</td>
<td>ON</td>
<td>2.45</td>
<td>6.82</td>
<td>6.71</td>
</tr>
<tr>
<td>8.00 - 16.00</td>
<td>8.00</td>
<td>ON</td>
<td>1.80</td>
<td>51.84</td>
<td>48.40</td>
</tr>
<tr>
<td>16.00 - 18.00</td>
<td>2.00</td>
<td>ON</td>
<td>2.00</td>
<td>14.40</td>
<td>12.32</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>12.00</strong></td>
<td></td>
<td></td>
<td><strong>88.72</strong></td>
<td><strong>74.04</strong></td>
</tr>
</tbody>
</table>

It could be concluded from the parameters in Table 4.4, that the discharge of the pump is not in the declared range to have a good efficiency, because of the poor water resources, resulting in increased power consumption. The performance of Submersible pump-set with flow control mechanism is given in Table 4.5.
### Table 4.5 Performance of Pump with Flow Control

<table>
<thead>
<tr>
<th>Time of operation</th>
<th>Duration (h)</th>
<th>Status of the Pump</th>
<th>Discharge (lps)</th>
<th>Quantity of water Pumped (kL)</th>
<th>Energy Consumed (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.00 - 6.30</td>
<td>0.50</td>
<td>ON</td>
<td>4.50</td>
<td>8.10</td>
<td>3.32</td>
</tr>
<tr>
<td>6.30 - 7.00</td>
<td>0.50</td>
<td>ON</td>
<td>4.20</td>
<td>7.56</td>
<td>3.29</td>
</tr>
<tr>
<td>7.00 - 7.30</td>
<td>0.50</td>
<td>ON</td>
<td>3.50</td>
<td>6.30</td>
<td>3.44</td>
</tr>
<tr>
<td>7.30 - 8.00</td>
<td>0.50</td>
<td>OFF</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>8.00 - 9.30</td>
<td>1.50</td>
<td>ON</td>
<td>4.00</td>
<td>21.60</td>
<td>10.17</td>
</tr>
<tr>
<td>9.30 - 10.00</td>
<td>0.50</td>
<td>ON</td>
<td>3.50</td>
<td>6.30</td>
<td>3.44</td>
</tr>
<tr>
<td>10.00 - 11.00</td>
<td>1.00</td>
<td>OFF</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>11.00 - 13.00</td>
<td>2.00</td>
<td>ON</td>
<td>3.50</td>
<td>25.20</td>
<td>13.58</td>
</tr>
<tr>
<td>13.00 - 14.00</td>
<td>1.00</td>
<td>OFF</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>14.00 - 16.00</td>
<td>2.00</td>
<td>ON</td>
<td>3.50</td>
<td>25.20</td>
<td>13.58</td>
</tr>
<tr>
<td>16.00 - 17.00</td>
<td>1.00</td>
<td>OFF</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>17.00 - 18.00</td>
<td>1.00</td>
<td>ON</td>
<td>3.50</td>
<td>12.60</td>
<td>6.87</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>12.00</strong></td>
<td></td>
<td></td>
<td><strong>112.86</strong></td>
<td><strong>57.69</strong></td>
</tr>
</tbody>
</table>

Following inferences could be made from Table 4.5:

- The quantity of water pumped got increased by 21.3% in half a day
- Energy consumption of submersible pump set got reduced by 28% for a 12 hour duration, with 21.3% more water discharge

This would help reduce the total electricity bill to be paid by the farmers. Farmers have to be educated on the conservation of water and electrical energy. If this intelligent system is fitted along with the submersible motor starter, will provide information on the water requirement to the
agriculture field and the energy requirement / consumed by the utility from
time to time; this will result in optimum utilization of electrical energy. The
decision making system should be supplied with the data on crop-pattern,
rain-fall-pattern and land-pattern for further improvement in energy
conservation. This system automatically shuts off the pump motor by sensing
the humidity and the moisture content of the land under irrigation.

4.5 COOLING OF SUBMERSIBLE MOTOR IN V6-TYPE
ASSEMBLY

The 3-phase squirrel cage Induction motor that is part of the
V6-type submersible pumps, has a slotted stator in which PVC-insulated
copper wire is inserted. The rotor consists of a series of skewed copper rods
welded together. Both the stator and the rotor are secured inside the water-
proof housing. The additional parts inside the housing are used to reduce the
run-out of the shaft.

Since the motor is not 100% efficient, a part of the power supplied
gets converted into heat (Joule Heating). This is detrimental to the life of the
motor. To remove the heat from the elements, the housing is filled with pure
water, so that no dirt particles block the clearance spaces between the rotor
and the stator. This heat, absorbed up by the water, gets transferred to the
ambient, and hence prevents the temperature rise inside the motor. Otherwise,
the heat may cause the insulation to melt and thereby short-circuiting the
wires. To enhance the heat transfer to the surroundings, the stator is covered
with a stainless steel casing. But, further efforts are necessary in order to
dissipate the heat effectively.

The key to increase the life of a submersible motor is to ensure
thermal conductivity at its best. Most submersible pumps rely on forced
convection in order to move heat away from the motor. The ambient/produced
fluid is typically drawn by the motor, in the course of pumping in order to accomplish this task. The maximum motor diameter and the minimum inside diameter of the well shall be in such a relationship that under any operating condition, the water velocity past the motor neither exceeds 5.7 m/s nor goes below 0.15 m/s.

Figure 4.14 Motor Jacket Installation with Cooling Sleeve

Figure 4.14 shows the motor jacket installation with cooling sleeve used by most of the pump manufacturers worldwide. The shroud of the motor is generally of the next nominal diameter of standard pipe larger than the motor or the pump, depending on the shroud configuration used. The tubular/pipe material can be plastic or thin-walled steel (corrosion resistant materials preferred). The cap/top must accommodate power cable without damage and provide a snug fit, so that only a very small amount of fluid can be pulled through the top of the shroud. The fit should not be completely water-tight as ventilation is often required to allow escape of the air or gas that might accumulate. The shroud body should be stabilized so as to prevent rotation and maintain the motor centered within the shroud. The length of the
shroud should extend to 1-2 times the diameter of the shroud beyond the bottom of the motor. Shrouds are typically attached immediately above the pump-intake or at the pump/column-correction. This type of sleeve is suitable to standard conditions; but for wide operating voltage bandwidth and poor water-resource areas, additional cooling mechanism is required so as to avoid the failure of insulation. It has been reported by motor manufacturers of Coimbatore that most of the insulation failure is at overhang portion of the winding due to poor cooling.

4.5.1 Cooling by Forced Convection with Axial Fan

Heat dissipation can also be enhanced by increasing the flow-velocity of the ambient fluid on the heat transfer surface. This process is called forced convection. Increase in the flow velocity increases the coefficient of convective heat transfer, which in turn increases the heat transfer rate. To achieve this, axial fan (intended to give high flow rate) is mounted on the shaft above the motor. For this, the length of the shaft needs to be increased. The fan sucks water from beneath the motor, allowing it to flow along the motor surface; finally, pushing it into the suction inlet of the pump. The following parameters have been considered for the design of 7.5-HP submersible motor pump-set cooling:

- Efficiency is of the order of 80 %
- Heat dissipated is $0.2 \times 7.5 \times 0.746 = 1.11 \text{ kW}$
- Speed of the motor is 2850 rpm
- Motor is placed 350 feet below the ground level
- Water temperature is 30°C
- The motor is assumed to be a constant temperature heat source
- Specific Speed ($N_s$) for an axial fan is 7000 rpm
• Head for the Axial fan is 2 m (little greater than the pump length)

• Motor Outer Diameter (D₁) is 140 mm

• Bore Diameter (D₂) is 165.1 mm

• Thickness of casing (tₖ) is 7 mm, and Length of casing (Lₖ) is 426 mm

• Thermal Conductivity of Cast Iron (Kₖ) is 80.13 W/m K

Properties of water at 30° C are:

• Density (ρₐ) is 995.7 kg / m³

• Dynamic Viscosity (μₐ) is 7.975 x 10⁻⁴ N-sec/m²

• Prandtl Number (Pᵣ) is 5.43

• Thermal Conductivity (kₚ) is 0.613 kW/m/K

The specific speed is given by Equation (4.1).

\[ N_s = \frac{\text{rpm} \sqrt{\text{GPM}}}{\text{H}^{0.75}} \]  \hspace{1cm} (4.1)

Substituting the values in Equation (4.1), the value of flow rate (Qₖ) is given by

\[ Q_f = 101.36 \text{ GPM} \]

\[ = 6.39 \text{ lps} \]

The area between the bore and the motor body (annulus) is given by Equation (4.2).
\[ \text{Annular Area} = \frac{\pi}{4}(D_2^2 - D_1^2) \quad (4.2) \]

\[ = 6.014 \times 10^{-3} \, m^2 \]

The velocity in the annulus is determined by Equation (4.3).

\[ \text{Velocity} = \frac{\text{Discharge}}{\text{Annular Area}} \quad (4.3) \]

\[ = 1.06 \, m/s \]

The hydraulic diameter \( (D_h) \) is the difference between the diameter of the pipe and the diameter of the motor body as given in Equation (4.4).

\[ D_h = D_2 - D_1 \quad (4.4) \]

\[ = 25.1 \, mm \]

The Reynolds number \( (R_e) \) is given by Equation (4.5).

\[ R_e = \frac{\rho v D_h}{\mu} \quad (4.5) \]

\[ = 33361.75 \]

Darcy’s friction factor \( (f) \) is given by Equation (4.6).

\[ f = (0.79 \ln(R_e) - 1.64)^{-2} \quad (4.6) \]

\[ = 0.023 \]
Nusselt number \((N_u)\) is given by Equation (4.7).

\[
N_u = \frac{f/\log(R_e-1000)/Pr}{1+127(L/\bar{\rho})^{0.5} (\rho_r/\rho_r-1)}
\]  

\[= 211\]  

The heat transfer coefficient \((h)\) is calculated using Equation (4.8).

\[
h = \frac{N_u k_w}{D_{ht}}
\]  

\[= 5.153 \text{ kW}(\text{m}^2\text{K})\]  

The overall heat transfer coefficient \((h_{oa})\) is determined by using Equation (4.9).

\[
h_{oa} = \frac{K_{ec} \times h}{h \times t_c + K_{CI}}
\]  

\[= 3.553 \text{ kW}(\text{m}^2\text{K})\]  

The heat to be dissipated \((H)\) and the surface area \((A_s)\) are calculated using Equation (4.10), and Equation (4.11), respectively.

\[
H = 0.2 \times 7.5 \times 0.746
\]  

\[= 1.119 \text{ kW}\]  

\[
A_s = 2 \times \pi \times 0.140 \times 0.426
\]  

\[= 0.37 \text{ m}^2\]  

The Temperature Difference \((\Delta T)\) is calculated by Equation (4.12)
\[ \Delta T = \frac{Q_f}{\dot{m} \cdot A} \]  
\[ = 1.68 \text{ K} \]

The following assumptions have been made in the design of the axial fan so as to increase the flow velocity:

- Usually, \( D_{\text{hub}}/D_{\text{tip}} \) is in the range of 0.3 to 0.6, and 0.55 is considered for this case.
- Inlet Pre-whirl = 0
- \( D_{\text{tip}} = 70 \text{ mm} \)
- Number of blades (\( Z_b \)) = 3

The diameter of the hub (\( D_{\text{hub}} \)) is calculated using the tip diameter (\( D_{\text{tip}} \)) and the ratio as given in Equation (4.13).

\[ D_{\text{hub}} = 0.55 \times D_{\text{tip}} \]  
\[ = 38.5 \text{ mm} \]

The flow area (\( A_f \)) between the hub and the tip of the fan is determined by Equation (4.14).

\[ A_f = \frac{\pi}{4} (D_{\text{tip}}^2 - D_{\text{hub}}^2) \]  
\[ = 0.002684 \text{ m}^2 \]

The meridional component (\( C_m \)) of the velocity in terms of discharge and area is calculated using Equation (4.15).
\[
C_m = \frac{\text{Discharge}}{\text{Area}} \quad (4.15)
\]

\[
= 2.38 \text{ m/sec}
\]

The blade tip velocities \(U_1\) and \(U_2\) at the hub (h) and the tip (t) at both the inlet (1) and the exit (2) are found by using Equation (4.16) and Equation (4.17), respectively.

\[
U_{1t} = U_{2t} = \frac{2850 \times 2 \pi \times 0.07}{2 \times 60} \quad (4.16)
\]

\[
= 10.44 \text{ m/sec}
\]

\[
U_{1h} = U_{2h} = \frac{2850 \times 2 \pi \times 0.0385}{2 \times 60} \quad (4.17)
\]

\[
= 5.745 \text{ m/sec}
\]

Both the Exit Whirl-hub (\(C_{u2h}\)) and the Exit Whirl-tip (\(C_{u2t}\)) are assumed as 19.6 m/sec, based on the axial fan head of 2 m.

The hub blade angle at the inlet is calculated using Equation (4.18).

\[
\beta_{1h} = \tan^{-1}\left(\frac{C_m}{U_{1h}}\right) \quad (4.18)
\]

\[
= 22.5^\circ
\]

The tip blade angle (\(\beta_{1t}\)) at the inlet is calculated using Equation (4.19).

\[
\beta_{1t} = \tan^{-1}\left(\frac{C_m}{U_{1t}}\right) \quad (4.19)
\]

\[
= 12.84^\circ
\]
The hub blade angle ($\beta_{2h}$) at the exit is calculated using Equation (4.20).

$$\beta_{2h} = \tan^{-1} \left( \frac{c_m}{u_{2h} - Cu_{2h}} \right)$$

(4.20)

$$= 45.46^\circ$$

The tip blade angle at the exit is calculated using Equation (4.21).

$$\beta_{2t} = \tan^{-1} \left( \frac{c_m}{u_{2t} - Cu_{2t}} \right)$$

(4.21)

$$= 15.53^\circ$$

From graphs (Stephanhoff), the vane spacing ratios at the hub and the tip are found to be 0.975 and 1.2675, respectively.

The vane spacing at the hub ($t_{hub}$) and the tip ($t_{tip}$) are determined by using Equation (4.22) and Equation (4.23), respectively.

$$t_{hub} = \frac{\pi D_1}{Z}$$

(4.22)

$$= 40.31 \text{ mm}$$

$$t_{tip} = \frac{\pi D_2}{Z}$$

(4.23)

$$= 73.33 \text{ mm}$$

The vane chord length of tip ($l_{tip}$) and the van chord length of hub ($l_{hub}$) are calculated using the vane spacing ratio and the vane spacing at the hub ($t_{hub}$), and the tip ($t_{tip}$) as:

$$l_{tip} = 71.46 \text{ mm}$$

$$l_{hub} = 39.30 \text{ mm}$$
The 3-D model of the axial fan, the new intermediate piece, and the axial fan assembly is shown in Figure 4.15. Assembly view of axial fan with the Motor is shown in Figure 4.16.

The aluminium die-casted axial fan is shown in Figure 4.17.
Figure 4.17 Axial Fan: Hand-casted Aluminum Model

The axial fan was fitted with the existing 7.5-HP submersible pump-set by using an additional intermediate piece as shown in Figure 4.18. The performance test was carried out in industry test-setup-sump with and
without axial fan, continuously for 12 hours at the head of 100 m. The results are given in Table 4.6.

Table 4.6  Comparison of Temperature-rise and Power-consumption with and without Axial Fan Cooling

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Duration (hour)</th>
<th>Temperature (ºC)</th>
<th>Input Power (kW)</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>With Axial Fan</td>
<td>Without Axial Fan</td>
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<tr>
<td>1</td>
<td>1</td>
<td>31</td>
<td>31</td>
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<tr>
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<td>12</td>
<td>41</td>
<td>49</td>
</tr>
</tbody>
</table>

Following inferences could be made from Table 4.6:

- After 12 hours of operation, the temperature of submersible motor with the axial cooling fan is 41ºC, compared to 49ºC without axial cooling fan.
- The power consumption in the case of motor with axial fan got increased by 180 W; however, the failure due to temperature raise could be avoided.
- Since forced cooling is available, the electrical loading (ac) value could be increased significantly in order to reduce the size of the Motor.