Chapter 5

Results and Discussions

5.1 Introduction

The main function of the developed 50 kW arc heater system is to heat the gases like nitrogen or argon, up to temperatures in excess of 2000 K, which in turn dissociates SF$_6$ into fluorine atoms [19, 27, 80]. The developed system has been interfaced with the Data Acquisition and System so that it can be controlled from PC through dedicated software. The DAS has operational control, acquisition, measurement, monitoring, display and storage of various parameters for optimizing its performance. Further the arc heater has been integrated with other subsystems of HF Laser. These include mixing chamber, supersonic nozzle, optical cavity, diffuser, scrubber and vacuum system. This chapter discusses the arc heater performance evaluation with respect to its capability of handling flow rates corresponding to a kilowatt laser power levels. The chapter also discusses in details, the experiments carried out and performance evaluation of arc tunnel system employing this developed arc heater.

5.2 Experimental Set-up

The developed experimental set up of HF laser tunnel along with 50 kW arc heater in operation is shown in fig. 5.1 below. The overall HF laser system consists of a gas handling system, dc arc heater and controls (DAS), a plenum, supersonic nozzle, an optical cavity, diffuser and vacuum dumps. A magnetic field coil is used to rotate the arc on anode periphery in addition to the vortex plasma gas entry. This tends to prevent overheating and erosion of electrode surfaces, increases the arc voltage for a given current, improves electrical stability and decreases electrical noise and pressure.
fluctuations. The arc is ignited either by shorting the electrodes with solder metal or by using a high frequency ignition unit. As shown in fig. 5.1, the optical axis is perpendicular to the gas flow direction. The 2” diameter quartz blanks have been mounted in mirror mounts on the optical used in place of ZnSe (as output coupler) and Si (total reflector) mirrors for initial testing of Arc heater. These blanks can easily be replaced with suitable optics for laser power extraction experiments.

**Fig. 5.1: Developed hardware and photograph showing arc heater**

The developed arc tunnel and DAS have been successfully interfaced and tested for HF laser. DAS fulfills the entire requirement to operate the research grade HF laser. In HF laser, arc plasma heater is an attractive tool for obtaining the high temperature necessary for dissociation of SF₆ (>2000 K). The energy from N₂ arc plasma is utilized to dissociate SF₆ in plenum so as desired number of fluorine atoms are generated for initiating the subsequent lasing reaction in the cavity. For a kW level HF arc-driven chemical Laser system, 1g/s flow rate of SF₆ is required in plenum to generate desired quantity of fluorine atoms and subsequently 1g/s of H₂ is added at the
nozzle exit plane to initiate the chemical reaction essential for lasing action. These flow rates are controlled and supplied to laser system with the help of DAS and desired conditions of lasing i.e. cavity pressure in the range of 5-10 mbar and plenum pressure of 1.5-2 bar need to be established. Normally during each run, the mass flow rate of each gas and pressure, plenum pressure and temperature, arc voltage and current, cavity pressure and temperature and cooling water flow rates are monitored from single control console and acquired through DAS for analysis and performance evaluation.

The essential conditions conducive for laser applications can be summarized as follows:

- Total mass flow rate: 7 – 8 g/s, out of which inert gas like nitrogen is 5 – 6 g/s and hydrogen and SF$_6$ are 1 g/s each.
- The temperature in arc region is of the order of 5000 K. The initiation of the arc itself corresponds to about 5000 K temperature of the arc.
- The temperature in the plenum region where SF$_6$ is mixed is in the range of 2000 K that is required for dissociation of SF$_6$.
- Plenum pressure should be in the range of 1 – 2 bar and cavity pressure should be in the range of 5 – 10 mbar.

Keeping these conditions in mind the testing and evaluation of arc heater and other laser related subsystems have been carried out. Initially the performance of Arc heater has been evaluated as a stand-alone system and later on the performance has been evaluated in conjunction with other subsystems.

5.3 Performance Evaluation of Stand alone 50 kW Arc Heater

As discussed in previous chapters, the 50 kW dc arc heater is designed and developed for realizing a kW level HF/ DF laser tunnel. It provides a highly energized
continuous plasma source of free electrons, positively charged ions and neutral atoms with energy equilibrium temperature in excess of 5000 K. The plasma is formed in a direct current electric arc and discharged to a plenum chamber for mixing other gases (such as nitrogen, sulfur hexafluoride and oxygen etc) for having temperature of lasing mixture about 2000 K. The energy level of plasma jet is controlled by the regulation of arc gas flow rates and input electrical power to the arc heater. As discussed, 50 kW arc heater is basically a forced water cooled, direct current arc device with a thoriated tungsten cathode and hollow cylinder made up of oxygen free high conductivity copper anode. The configuration is free arc length, cylindrical concentric design.

In the performance evaluation to be discussed herein, following parameters have been studied.

- Efficiency
- Effect of constriction to study the suitability of arc heater for high pressures
- Arc heater life related studies
- Suitability of arc heater for required flow rates

Three variables were independently controlled, namely, (1) the gross power input PG (2) the gas mass-flow rate m, and (3) the nozzle throat diameter (constriction). These quantities necessarily introduce the variables such as the arc potential difference V and current I (VI=PG), the stagnation pressure P_o in the arc chamber, and the net power to the gas W. The data were cross-plotted so that the absolute variation of the important arc characteristics with the basic parameters could be determined.
5.3.1 Arc Heater Efficiency

Arc heater efficiency is defined as ratio of the power to the gas divided by the gross arc power fed into the arc heater as per the equation 5.1

\[ \eta = 100 \left( 1 - \frac{PC + PA}{PG} \right) \% \] (5.1)

PC  = Cathode power losses in kW
PA  = Anode power losses in kW
PG  = Gross power input in kW

Since efficiency of 50 kW arc heater is primarily concerned with the losses of electrodes, the losses of the cathode, cathode chamber (water-cooled section that separates the anode and cathode), anode, plenum, and nozzle are considered separately. The anode heat loss includes the usual product of anode sheath potential difference and the current in addition to the forced-convection loss of heated gas. There is also radiation from the arc to the cold wall, which is believed to be relatively small. A detailed analysis shows that losses vary with the basic operating parameters, pressure, arc power input, and gas flow rates. The temperature rise of cooling water through the various arc heater components is measured throughout the arc operation on DAS by taking inputs from RTDs employed for this purpose. The efficiency evaluation of 50 kW arc heater is based on the computation of gas power by simple calorimetric technique in which losses to the cooling water are subtracted from the electrical input power to the arc heater and power in the inlet gas before heating. The following basic measurements were made for this evaluation

1. Arc Voltage and Current
2. Inlet gas temperature and pressure
3. Gas flow rates
4. Cooling water temperature increase

5. Water flow rates

Water flow rates are measured using calibrated turbine type flow meters. Whereas the gas flow rates are taken from thermal and carioles flow meters and are fed to DAS for analysis.

The table 5.1 below shows the different conditions of flow rates and pressures of nitrogen for achieving arc input power levels of 50 to 55 kW. Input power levels were kept in this range by varying the feed pressure, constriction size and chamber pressure. Experiments were carried out for 70 seconds duration to establish the steady state conditions. The water circulated was at flow rates of 45 liters/ min and 23 liters / min through anode and nozzle chambers respectively. It may be mentioned that the cathode loss is small (of the order of 5% of the total arc power) for thoriated tungsten and thus has not been considered while calculating the efficiency of arc heater. The cathode chamber is exposed to radiation from the arc, and this heat loss may also be of the same order of magnitude as that of the cathode.

It is evident from the results that the nozzle losses are comparatively less than the anode losses, as maximum water temperature rise of 2.3 °C of nozzle chamber was observed at 54.4 kW arc input power level. The other important observation is that heat loss of the anode decreases with increasing flow rate and increases with increasing gross power input. This similar trend is also reported in the literature. However, the efficiency goes down with the increase of arc current.

Increase in Temperatures was recorded for different runs. The efficiency was estimated for 70 seconds run times as water temperatures are taken from RTDs and temperatures stabilize by that time.
Table 5.1: Experimental Results on 50 kW Arc Heater

The efficiencies achieved are in range of efficiency values given between 40-50% for non-transferred arc plasma torches as reported in the literature [68]. Further the efficiency increases with the increasing arc power but decreases with increasing currents. Fig. 5.2 below depicts the efficiency with increasing arc input power on 50 kW arc heater with nitrogen buffer gas. The results show that thermal efficiency of the arc heater ranges from 42 to 45 in 50 kW Arc heater, which means that more than half of the total power input taken away by the cathode and anode cooling water.

![Graph showing efficiency as a function of arc input power](image)

Fig. 5.2: Efficiency as a function of arc input power

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These studies support the initial calculations carried out in chapter 2 where the efficiency of arc heater was assumed to be 40 – 50 % to arrive at its power requirements needed for a kilowatt HF laser.

5.3.2 Effect of Arc Constriction

The purpose of these studies is to simulate conditions to test the arc heater for its suitability for high pressures of the order of 1.5 – 2.0 bar encountered in HF lasers. Further, these studies can also reveal whether this arc heater can be used for still higher pressures of the order of 20 – 25 bar usually encountered in other gas dynamic lasers like carbon dioxide. The constriction of arc jet is realized by using different sizes of nozzles fixed at the exit to allow the hot gases to the atmosphere. The constriction process of arc results in high chamber pressure and improvement in heat flux values. The constriction of arc was initially studied with nozzles of sizes 6 mm, 5 mm and 3 mm. Fig. 5.3 shows the variation of chamber pressure as a function of feeding pressure for these three nozzles. It can be observed that that the 3 mm nozzle is suitable for simulating arc chamber pressure requirements of about 2 bar for HF laser work. It results in increase in pressure of arc chamber in the range of 1.5 to 1.9 bar depending on the feed pressure which in turn is related to the flow rates.

![Plot of chamber pressure variation](image)

**Fig. 5.3:** Variation of chamber pressure for various nozzles
Further, in order to see whether the arc chamber can handle required flow rates at these pressures of 1.5 – 2 bar, experiments were carried out on 50 kW arc heater using 3 mm nozzle. Mass flow rates in the range of 1 g/s to more than 15 g/s were varied by changing the feed pressure of nitrogen gas. These results are shown in fig. 5.4. It can be observed that the demand for arc voltage requirements increases linearly with mass flow rates of N₂ in 3 mm nozzle. This is expected also because with the increase in flow rates require higher powers for initiation of the arc.

![Arc Voltage v/s Nitrogen Flow](image)

Fig. 5.4: Arc Voltage requirement for increasing flow rates

The pressure and temperature sensors accuracies are in the range of 0.2%. The Mach number has been calculated and uncertainty is of the order of 0.1%. It may be mentioned here that experimental points are within the errors shown in the plots.

Since for a given mass-flow rate the plasma pressure is primarily a function of the nozzle throat diameter, the independent effect of stagnation pressure on arc heater performance is obtained by using nozzles of various throat diameters. The number of nozzles required in such an evaluation depends on the nature of the variation of the parameters with pressure. For instance, if maximum limit has to be determined then it may require the use of several nozzles. Though the 50 kW arc heater has been designed to work mainly for HF lasers (1.5 – 2 bar), however, care has been taken to
choose the wall thickness so that it can be used for pressure up to 25 bar. It will make this arc heater a versatile device and may be used for other arc driven lasers in the laboratory. Keeping this in mind, the arc heater performance was studied at different pressures and flow rates conditions. Smaller size nozzles (2.4 mm, 2 mm, 1.75 mm and 1.5 mm) were also developed and number of experiments was carried out to study the arc behaviour at higher pressures.

To study the arc operation at higher pressures, experiments were carried out with smaller sizes of nozzles. Fig. 5.5 shows the arc voltage requirements with changing mass flow rates at high pressures. The arc operation at 10 bar was established with nozzle size of 2.4 mm at arc input power of 62 kW and N₂ mass flow rate of 2.5 g/s. The arc heater operation, however, was established up to maximum pressure of 25 atmospheres with nozzle size of 1.75 mm at arc input power of 56 kW and N₂ mass flow rate of 4.8 g/s.

![Arc Voltage v/s Gas Flow Rate](image)

Fig. 5.5: Arc Voltage requirement for different pressures

*These studies indicate that the developed Arc heater can very well be used for HF laser applications with the required flow rates. Further it can also be used for other*
arc driven lasers like carbon dioxide lasers in the laboratory with mass flow rates of the order of 5 g/s.

5.3.3 Arc Heater Life related Studies

As mentioned earlier a magnetic field coil is incorporated on the anode for distribution of the anode heat load over large area. In this way the lifetime of the anode is increased and the level of contamination of the plasma is reduced. In order to further reduce electrode wear, electrodes are over-protected by efficient cooling systems. A 20 hp multi-stage centrifugal pump capable of giving 300 liter/min de-ionized water flow rate at 10 bar is employed for efficient cooling of electrodes. This measure, however, reduces the efficiency to some extent of the arc plasma heater, which may be undesirable, especially for the long duration continuous operation of high power arc plasma heaters for other industrial applications. But for arc operation for short durations of the order of 10s of seconds, as is the situation in the present case, efficient cooling at the cost of slightly low arc plasma heater efficiency is acceptable for continuous wave HF/DF chemical laser application.

Further to study the contamination of arc plasma due to electrodes erosion, the 50 kW arc heater was subjected to long duration runs. Table 5.2 shows the experimental results of long duration runs of 4-5 minutes with low arc input power and at 50 kW power levels. The rise in anode and cathode cooling water temperatures were recorded. The maximum temperature rise of 9.3 °C with arc input power level of 51.45 kW was recorded for arc duration of 4 minutes. This temperature rise is below the designed temperature rise of 10 °C and there was no significant erosion of electrodes.
With low power levels:

<table>
<thead>
<tr>
<th>Flow Rate g/s</th>
<th>Chamber pressure kg/cm²</th>
<th>Anode Temp. Rise °C</th>
<th>Cathode Temp. Rise °C</th>
<th>Time Min.</th>
<th>ARC Voltage (volts)</th>
<th>ARC current (Amp.)</th>
<th>Power kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38</td>
<td>1.15</td>
<td>4.4</td>
<td>2.9</td>
<td>5</td>
<td>62</td>
<td>270</td>
<td>16.74</td>
</tr>
<tr>
<td>0.588</td>
<td>3.0</td>
<td>5.1</td>
<td>3.2</td>
<td>5</td>
<td>68</td>
<td>278</td>
<td>18.91</td>
</tr>
<tr>
<td>2.5</td>
<td>3.0</td>
<td>6.0</td>
<td>3.1</td>
<td>4</td>
<td>78</td>
<td>284</td>
<td>22.1</td>
</tr>
</tbody>
</table>

With 50 kW power:

<table>
<thead>
<tr>
<th>Flow Rate g/s</th>
<th>Chamber pressure kg/cm²</th>
<th>Anode Temp. Rise °C</th>
<th>Cathode Temp. Rise °C</th>
<th>Time Min.</th>
<th>ARC Voltage (volts)</th>
<th>ARC current (Amp.)</th>
<th>Power kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.58</td>
<td>4.3</td>
<td>8.9</td>
<td>1.4</td>
<td>5</td>
<td>163</td>
<td>308</td>
<td>50.2</td>
</tr>
<tr>
<td>2.7</td>
<td>4.8</td>
<td>8.6</td>
<td>1.5</td>
<td>4</td>
<td>175</td>
<td>294</td>
<td>51.45</td>
</tr>
<tr>
<td>5.8</td>
<td>6.1</td>
<td>8.3</td>
<td>1.8</td>
<td>4</td>
<td>184</td>
<td>289</td>
<td>53.2</td>
</tr>
<tr>
<td>6.7</td>
<td>6.9</td>
<td>8.1</td>
<td>2.3</td>
<td>4</td>
<td>188</td>
<td>285</td>
<td>53.6</td>
</tr>
</tbody>
</table>

Table 5.2: Long Duration Arc Heater Experiments

The above-mentioned studies reveal that the developed Arc heater can be used even for long duration runs without degradation in its performance.

5.3.4 Performance of Arc Heater for Required Flow Rates

The single most important characteristic of the electric arc is that of its voltage-current relationship for a fixed arc gap. This relationship for any given arc is a function of many factors, such as anode and cathode material, gap spacing, ionizing gas mass flow and operating environment; however, it is possible to describe a quantitative curve, which is characteristic of all non-transient electric areas. Such a curve displays a negative slope (decreasing voltage with increasing current) at low current and slight positive slope (increasing voltage with increasing current) after a minimum voltage is reached.

The minimum voltage \( V_{\text{min}} \) corresponding to natural arc length is given by

\[
V_{\text{min}} \propto m p^k / D^n I
\]  

(5.2)

Where:

\( m \) = mass flow rate through arc duct
P = pressure in arc duct

I = Arc Current

k = exponent depending upon gas conditions (¼ to ½)

n = exponent depending on arc plasma gas used (1.7 for nitrogen)

D = Duct diameter

It is established from the above relation that minimum voltage corresponding to natural arc length is inversely proportional to the arc current.

An ordinary electric arc without forced convection has definite intrinsic properties. However, mass flow of gas through the arc chamber represents a new, independent parameter not present in ordinary arcs with natural convection. Also it has been observed that at fixed mass flow rate, the arc voltage is relatively insensitive to arc currents. To study the voltage-current behavior of arc over wide range of parameters, the arc heater operation with changing mass flow rates, pressures and power levels were carried out. The performance of arc heater has been studied with the help of developed DAS. The mass flow of gas through the arc chamber is varied with gas feed system and voltage & current have been acquired by DAS. The arc behavior was studied with argon and nitrogen gases at various mass flow rates, arc input powers and pressures. The representative voltage-current characteristics for few mass flow rates of argon and nitrogen are shown in fig. 5.6 and fig. 5.7 shows detailed variations with nitrogen mass flow rates. Voltage-current plots indicate that voltage required for arcing in diatomic gas like Nitrogen is more than the monatomic gas Argon. Also an increase in the mass flow rates at constant arc current produces an increase in the arc voltage, increase in the pressure and reduction in the static enthalpy at simultaneous increases in the efficiency. At fixed mass flow, the arc voltage is observed to increase in proportion to a fractional (1/4 to ½) power of the arc chamber.
pressure. The value of the pressure exponent is an empirical function of the arc configuration and operating conditions.

Fig. 5.6: V-I plot at changing mass flow rates with Ar & N₂

Fig. 5.7: V-I plot at changing mass flow rates with N₂
It can be further seen from fig. 5.6 that for a given mass flow rate, the power requirement for initiation of arc is almost 50% less in case of argon as compared to nitrogen. This means that for the required flow rates of 5 – 6 g/s, the power requirement will be significantly less implying that heat content may not be sufficient for dissociation of SF6 into fluorine atoms.

Although the arc heater operation is characterized with argon and nitrogen buffer gases, but for HF laser operation only nitrogen gas is used because the enthalpy content of nitrogen is 2.7 times more than argon at 5000 K. Further experiments were carried out with nitrogen only to establish voltage-current requirements for desired mass flow rates.

The typical voltage-current characteristic for a 50 kW power level for nitrogen is shown in fig. 5.8 below. It is evident that arc is negative resistance load; that is why special power sources with drooping characteristics (i.e. welding generators/rectifiers) have been used for stable arc operation.

![V-I on 50 kW Arc Heater](image)

**Fig 5.8: V-I Characteristic of 50 kW Arc Heater with N₂**
5.4 Experiments on 50 kW Arc Tunnel

The evaluation of Arc heater as a stand alone device has clearly demonstrated that it fulfills all the requirements like handling of power at required flow rates, pressures etc and thus can be used for Arc driven HF laser applications. The Arc heater has been integrated with plenum, supersonic nozzle, optical cavity, diffuser, scrubber and vacuum system. The experimental set up for conducting laser experiments on 50 kW arc tunnel is shown above in fig. 5.1. Arc-heated nitrogen is used for dissociation of SF₆ in order to create F-atoms. Hydrogen is diffused at the Nozzle Exit Plane (NEP) into the supersonic flow containing F-atoms. The reaction of H₂ and F-atoms creates vibrationally excited HF in the cavity. The mounts for mirrors are placed 80 cms apart on the laser axis transverse to main flow. The operation for arc tunnel is done from single control console from remotely located control room for the safety reasons.

In all the experiments related to arc tunnel reported here, 5 – 6 g/s of nitrogen gas was flowing though the arc heater.

5.4.1 Plenum Temperature

The gas mixture temperature in the upstream at plenum is an important parameter for having desired temperature and pressure conditions for lasing. The necessary F atoms are generated in plenum by mixing arc heated nitrogen and SF₆ such that the mixture temperature is in excess of 2000 K. At these temperatures the SF₆ dissociates with F among the products. The nitrogen, fluorine atoms and other dissociation products are then expanded through supersonic wedge nozzle to the entrance of laser cavity. At that point, hydrogen is injected to have HF excited. Fig. 5.9 shows the fall in temperature by increasing mass flow rate of SF₆ in plenum. It can be observed that though the plenum temperature decreases with the increase in flow rate of SF₆, yet it
is always in the range of 2000 K even for one g/s ensuring the dissociation of SF₆ and production of fluorine atoms.

Fig. 5.9: Fall in Plenum Temperature with SF₆ addition

5.4.2 Effect of SF₆ and H₂ Gas Flow Rates

For a kW level HF laser system, 5-6 g/s of nitrogen flow rate is desirable from 50 kW arc heater system. SF₆ is added in the plenum where it comes in contact with the hot nitrogen plasma and gets dissociated into F-atoms. Fig. 5.10 shows the variation in arc power with change in SF₆ flow rates.

Fig. 5.10: Variation of arc power with SF₆ flow
It is evident from fig. 5.9 that the developed arc heater is capable of handling $SF_6$ flow rates of the order of 1 g/s required for a KW HF laser.

As mentioned earlier in chapter 3, the hydrogen gas is diffused in supersonic stream at the exit of nozzle. The hydrogen injection is done through 20 hydrogen-feeding nozzles attached to the cavity flange. The total mass flow rate of hydrogen required is 1 g/s for kW power level. The arc input power requirement was also studied with change in hydrogen flow rate. Fig. 5.11 shows the arc input power required for change in hydrogen mass flow rate.

![Arc Power Vs H₂ Flowrate](image)

Fig. 5.11: Variation of arc power with H₂ flow

It can be observed from fig. 5.11 that the Arc heater can handle flow rates of hydrogen up to 1 g/s in addition to 5 – 6 g/s of nitrogen.

5.4.3 Estimation of Mach number

The desired Mach No in gas mixture is achieved with special supersonic converging/ diverging nozzle attached to plenum of the tunnel. Mach number has been estimated with the help of acquired cavity ($P_c$) and plenum ($P_0$) pressure using