An Experimental Study on Dielectric Properties of Gyrotron RF Window Coolant

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Abstract- A 200 kW, 42 GHz Gyrotron is designed for the controlled plasma fusion experiment in India. In this paper the results of dielectric properties measurements of FC-75 (Fluoro Carbon-75) are presented, which is used in the double disk RF window of gyrotron as a coolant. The dielectric constant, the dielectric loss and the relaxation time are measured from 1 GHz to 50 GHz. The measurement procedure is performed by dielectric probe kit by using 50 GHz Vector Network Analyzer. The experimental results are in good agreement with design aspects of RF window.

Index Terms: Dielectric constant, Dielectric loss, Relaxation time, Gyrotron.

I. INTRODUCTION

Gyrotron is the only high power, high frequency millimeter wave source, which is used in the electron cyclotron resonance heating (ECRH) in plasma fusion [1]. Recently, in India, a program related to design and development of 42 GHz, 200 kW gyrotron has been started [2]. Operating mode of this Gyrotron is TE03 and the gyrotron is to be used in an Indian Tokamak system for plasma heating. The basic specifications of the gyrotron are shown in Table 1.

RF window happens to be the most critical and vulnerable component in any high power microwave/millimeter wave vacuum device, which limits its power handling capability. The RF loss in the window material depends on the material dielectric properties. Sapphire (Al₂O₃) has been chosen as the window disk material. Different kind of heat transfer schemes can be adopted depending on the material thermal properties as shown in Fig. 1.

Table 1: Basic specifications of the gyrotron

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (f)</td>
<td>110 GHz</td>
</tr>
<tr>
<td>Output power (P₀)</td>
<td>1 MW</td>
</tr>
<tr>
<td>Interaction efficiency (η)</td>
<td>&gt;35%</td>
</tr>
<tr>
<td>Beam voltage (V₀)</td>
<td>80 kV</td>
</tr>
<tr>
<td>Beam current (I₀)</td>
<td>40 A</td>
</tr>
</tbody>
</table>

Fig.1. Cooling schemes for high-power mm wave windows
These are: (i) multiple dielectrics with distributed cooling, (ii) single disc with edge cooling, (iii) single disc with surface cooling by gas and (iv) double disc with surface cooling by liquid as shown in Fig.1.[3,4]. Each of these designs possesses its own advantages and disadvantages. The double disc face cooled structure causes power loss in two discs. In addition, loss in the coolant also has to be taken into account. However, as far as cooling of dielectric is concerned; this is the most effective design. Double disc with surface cooling by liquid is designed for 42 GHz gyrotron.

Emboldened with these results, the double sapphire disc window geometry with FC-75 face cooling has been unanimously accepted for the first Indian gyrotron program. The FC-75 is a perfluorocarbon derivative of the tetrahydrofuran with chemical formula $C_{8}F_{16}O$. The IUPAC name of this compound is 2,2,3,3,4,4,5-heptafluoro-5-(1,1,2,2,3,3,4,4,4-nonafluorobutyl) tetrahydrofuran. Its molecular structure is shown in Fig.2. Physical properties of this compound are given in Table- 2.

![Fig.2. Molecular structure of FC-75](image)

The reflection and absorption of RF power depends on the dielectric properties of FC-75. Therefore, dielectric constant and dielectric loss of FC-75 have been measured in wide frequency range from 1 GHz to 50 GHz.

### Table 2: Physical Properties of FC-75

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point ($^\circ$C)</td>
<td>102</td>
</tr>
<tr>
<td>Pour point ($^\circ$C)</td>
<td>-88</td>
</tr>
<tr>
<td>Vapour pressure (Pa)</td>
<td>$4.13 \times 10^3$</td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>1770</td>
</tr>
<tr>
<td>Vol. exp. coefficient ($^\circ$C$^{-1}$)</td>
<td>0.0014</td>
</tr>
<tr>
<td>Specific heat (J kg$^{-1}$C$^{-1}$)</td>
<td>1050</td>
</tr>
<tr>
<td>Kinematic viscosity (mm$^2$/s)</td>
<td>7.4</td>
</tr>
<tr>
<td>Absolute viscosity (cP)</td>
<td>1.4</td>
</tr>
<tr>
<td>Heat of vaporization @B.P (J/g)</td>
<td>88</td>
</tr>
<tr>
<td>Dielectric strength (kV/mm)</td>
<td>16.0</td>
</tr>
<tr>
<td>Volume resistivity (Ω cm)</td>
<td>$8.0 \times 10^{16}$</td>
</tr>
<tr>
<td>Inflammability</td>
<td>Non-flammable</td>
</tr>
<tr>
<td>O$_3$ Depletion potential (ODP)</td>
<td>Zero</td>
</tr>
<tr>
<td>Toxicity</td>
<td>Low</td>
</tr>
</tbody>
</table>

II. DESCRIPTION OF EXPERIMENTS

Dielectric properties of FC-75 have been measured by performance dielectric probe kit [5]. This performance dielectric probe kit is based on the reflection method. During the measurements, Vector Network Analyzer (VNA), ranging from 200 MHz to 50 GHz has been used as a power source [6]. The experimental set-up is shown in Fig 3. The measurements are made by simply immersing the probe into the FC-75 liquid. The complete system is based on a network analyzer, which measures the material’s response to RF or microwave energy. The probe transmits a signal into the material under test and received the reflected signal from the material. FC-75 is a volatile liquid. Hence, adequate measures are necessary for preventing its evaporation loss.

The relaxation time $\tau$ is calculated by using the formula [7]:

$$\tau = \frac{\varepsilon''}{\omega \varepsilon'}$$

Where $\varepsilon ''/ \varepsilon'$ is the loss tangent and $\omega$ is the angular frequency.
With the help of measured data of loss tangent and dielectric constant, the relaxation time has been calculated.

Fig. 3. Dielectric property measurement set up for 1GHz to 50GHz frequency range.

III. RESULTS AND DISCUSSION

The dielectric properties of FC-75 have been studied at various institutes at low frequency [8, 9]. Due to the unavailability of the dielectric properties data of FC-75 at higher frequencies, the measurement at the higher frequency (upto 50 GHz) has been performed. The dielectric constant and the loss tangent of FC-75 from 1 GHz to 50 GHz are shown in Fig. 4 and Fig. 5, respectively. The dielectric constant of FC-75 is approximately constant in a wide frequency range (1 GHz to 50 GHz). The dielectric loss of FC-75 is increasing with frequency. The value of dielectric loss rise from 0.01 to 0.04 as frequency increasing from 1 GHz to 50 GHz. The relaxation time is decreasing with frequency as shown in Fig. 6. The result shows the very small value of dielectric loss of FC-75 at 42 GHz, which is required to minimize the RF loss in window. Therefore, double sapphire disc window geometry with FC-75 face cooling has been unanimously accepted for the first Indian Gyrotron. To the best knowledge of the authors, the dielectric properties measurement of FC-75 has been carried out upto the 25 GHz [8, 9]. The obtained results of the dielectric constant and the loss tangent up to 50 GHz are in good agreement with the previous results shown as in Fig. 4 and Fig. 5. From the measurements, it is clear that the FC-75 can be used for other frequency gyrotrons like 24 GHz, 28 GHz industrial gyrotron, 35 GHz gyrotron for RADAR and whether applications and 42 GHz gyrotron for ECRH application.

Fig.4. Variation of dielectric constant with respect to frequency.

Fig.5. Variation of dielectric loss with respect to frequency.
IV. CONCLUSION

Low-power dielectric characterization of FC-75 has been done using dielectric probe kit method. We have achieved appropriate values of dielectric constant and dielectric loss of FC-75 at gyrotron operating frequency. The measurements are non-destructive and can be made in real time. The dielectric properties measurement of FC-75 in wide frequency range will be helpful for the gyrotron community as well as in the field of remote sensing.

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