Regeneration of Cryosorbing Exhaust Gas Panels by Means of Gyrotron Radiation

A. Möbius [a)] A. Mack [b)], C. Day [b)], G. Dammertz [c)], R. Wacker [d)]

[a)] IMT-GmbH, Erfurter Ring 15, D-76344 Eggenstein, Germany
[b)] Forschungszentrum Karlsruhe, Institut für Technische Physik, PO Box 3640, D-76021 Karlsruhe, Germany
[c)] Forschungszentrum Karlsruhe, Institut für Hochleistungsimpuls- und Mikrowellentechnik, PO Box 3640, D-76021 Karlsruhe, Germany
[d)] Universität Stuttgart, Institut für Plasmaforschung, Pfaffenwaldring 31, D-70565 Stuttgart, Germany

I. TASK

The exhaust gas of the planned fusion reactor ITER [1] consists of up to 10% helium and 90% hydrogen. The extraction of these gases from the reactor space is achieved by cryopumps comprising several cryogenically cooled flat panels having in total an absorbing surface of about 35 m². As can be seen in the cross section of a panel (figure 1) a 4 K cooled quilted steel plate is covered with activated carbon grains - serving as the absorbing material - glued onto the metal surface. In periodic cycles the pump has to be disconnected from the vessel and rapidly heated (during 75 s) to 80-100 K to regenerate the surface. After heating, rapid cooling down to cryogenic temperatures in also 75s is necessary. If the heating and cooling is performed by just changing the temperature of the coolant, the energy consumption is extremely high.

The panel has a thin wall design in the aim to keep the overall heat capacity low. The individual layers can be seen in figure 1, however it should be mentioned that the carbon consists of grains between 0.4 and 1 mm diameter. For each layer, table 1 shows the mechanical density, the average thickness and the weight per surface. Close to cryogenic temperatures the heat capacity and heat conductivity varies over several decades [2]. By integrating over the heat capacity the amount of energy necessary to heat the individual layers to 80 K is calculated and also shown in table 1. These numbers have to be compared to the required power to desorb the extracted gases which is about 5 kJ/m².

Table 1. Material properties.

Property	Coal	Glue	Steel
Mechanical density [kg/m³]	460	2000	7900
Thickness [mm]	1	0.3	1
Weight [kg/m²]	0.45	0.74	7.9
Q (80 K)/A [kJ/m²]	1.52	4.6	47.1

To exclusively heat the carbon and glue layer consumes roughly as much power as the desorption process needs which however in total is less than 20% of the power needed to heat the entire panel. As a possible heating method infrared radiation has been investigated, however, due to weak absorption with no success [3]. Here we investigate the application of microwave radiation to heat exclusively the carbon layer. The real and imaginary part of different kinds of carbon at room temperature varies between 1.6 to 3.5 and 0.08 and 0.31, respectively [4].

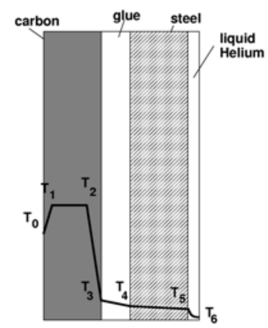

Fig. 1. Cross-section of the panel and corresponding temperature profile.

II. EXPERIMENTS

First experiments were performed at a frequency of 2.45 GHz. The first part of the tests were performed with loose activated carbon particles, inserted in a non-absorbing container. Measurements were done at room temperature, and repeated with the particles immersed into liquid nitrogen. However, the carbon did not show any difference in absorption behaviour at these two temperatures. A heating efficiency of about 50% had been estimated. Pyrometric measurements showed that the centre grain particles had been heated to more than 300 ^{0}C while the nonabsorbing container remained at cryogenic temperatures. In the second part of the tests, panel mock-ups with the set-up according to figure 1 were exposed with the carbon side to the same microwave radiation, which, however, lead to an absorption efficiency of a few percents only. This has been due the low thickness of the carbon layer compared to the high penetration depth.

The penetration depth can be reduced by using a higher frequency, i.e. gyrotron radiation that is available at most fusion reactor experiments. First high power experiments performed at the 140 GHz using the FZK-Thales gyrotron qualitatively showed that rapid heating is possible. The overall power was about 100 kW during a few milliseconds. Low power experiments at the same frequency were performed at IPF at various angles of incidence and polarisation. At an angle of 45°, the absorption was estimated to be about 64% (perpendicular case), and 84% (parallel case), respectively.

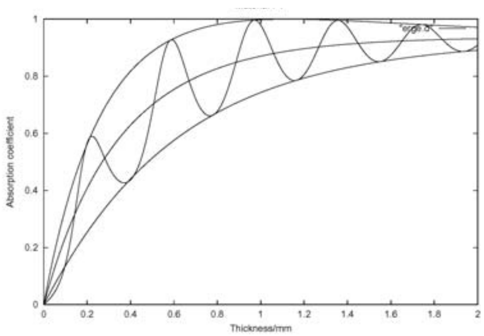

Fig. 2. Absorption coefficient vs. carbon thickness.

III. THEORY

A theoretical investigation to understand these results consists of electrodynamic and heat flux simulations. To find the appropriate approach we first calculated the penetration depth for different kinds of carbon at 140 GHz to be between 20 and 4 mm. This still is larger than the thickness of the carbon layer, which means both the reflection of the microwaves Γ_0 at the air-carbon boundary as well as the reflection at inner boundaries have to be taken into account. For first order calculation a scattering matrix formalism is used. The following assumptions are made:

- Due to unkown parameters the layer of glue is not taken into account.
- The boundaries between carbon and air and between carbon and stainless steel are flattened
- The stainless steel is considered to be perfectly conducting.
- The carbon dielectric parameters, measured at 2.45 GHz are also valid at 140 GHz.

This means we limited the analysis to a carbon layer of thickness d on a metallic surface. The individual scattering matrices caused by the abrupt change of the material parameters at the boundary carbon-air and the finite thickness of the carbon layer have been combined which lead to the overall reflection coefficient, given by:

$$\Gamma_{tot} = \frac{\Gamma_0 - e^{2ikd}}{1 - \Gamma_0 e^{2ikd}}$$

where k is the complex wavenumber in the carbon. Since the local thickness of the carbon layer is unknown figure 2 shows the absorption coefficient for a layer thickness of 0-2 mm. As a result we obtain a steep curve - that asymptotically approaches the input reflection coefficient Γ_0 as the thickness of the layer grows - superimposed by an oscillatory function which is due to the positive and negative interference of the reflection at the two boundaries. This is in good agreement with the measurements at IPF. Figure 3 shows the energy density of the electric field component in the carbon layer of 1 mm thickness. This power distribution has been taken as input parameter for the heat flux calculations.

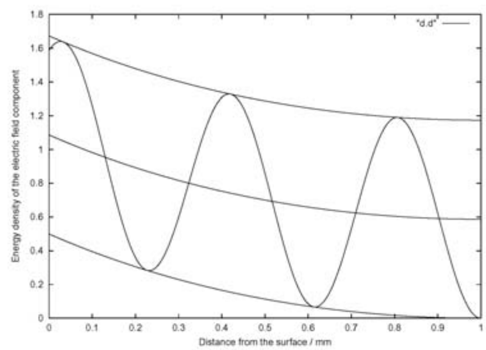

Fig. 3. Energy density of the electric field component inside the carbon layer.

For the non stationary heat flux calculation the well known Fourier´s law and the continuity equation have been solved numerically. Due to the extremely strong dependence of the heat capacity and conductivity the time steps had to be chosen extremely small. Extensive simulations showed that at least half of the heat generated in the carbon serves for the desorption of the fusion exhaust gas. Thus the helium consumption could be reduced down to 15-20% as compared to conventional heating. A typical temperature profile can be seen in figure 1.

IV. OUTLOOK

Further investigations have to include

- measuring the material parameters of the active carbon at liquid helium temperatures,
- building a test setup under vacuum,
- optimise the process parameters such that arcing is avoided during the process.

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