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Thermographic determination of the sheath heat transmission coefficient in a high density plasma

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ABSTRACT

Experiments were performed in the Pilot-PSI linear plasma device, to determine the sheath heat transmission coefficients in a high recycling regime under various conditions of density ($1–20 \times 10^{20}$ m^{-3}) and plasma composition (H_2, Ar, N_2) relevant for the ITER divertor plasma. The 2D surface temperature profile on a tungsten surface was measured with high spatial (0.33 mm) and temporal (200 Hz) resolution using an infrared camera. The target heat flux is calculated using a 2D axis-symmetric Ansys model, the heat transfer is determined from target calorimetry. The plasma parameters are measured with a high resolution Thomson scattering system located 17 mm away from the target surface. Radial profiles of the sheath heat transmission factors can thus be determined.

Preliminary results show that γ varies between 4 and 40 depending on the plasma conditions and composition. The value derived from the heat flux calculated with Ansys is significantly lower than theory predicts.

1. Introduction

The study and quantification of heat loads to plasma-facing components both in terms of magnitude and spatial distribution is of high importance for the design of future devices as it impacts on the components lifetime. The heat flux to a surface can be experimentally determined from infrared thermography, thermocouples and Langmuir probes. Each of those methods presents inherent advantages and drawbacks. Infrared measurements provide excellent spatial and temporal resolutions but can be affected by plasma-induced surface modifications and reflections from surrounding surfaces [1]. The determination of heat fluxes from Langmuir probes relies on the sheath-heat transmission coefficient (γ), which links the incoming heat flux and the plasma parameters at the surface [2]. γ depends on the ratio of ion and electron temperature, secondary electron emission, ion mass, particle reflection coefficients, recombination energy, etc. Its determination for multi-species plasma such as the divertor plasma in ITER is hence not straightforward.

The Pilot-PSI device provides a unique advantage for studying plasma surface interaction; it produces plasma with ITER relevant densities and temperatures, and a well-diagnosed environment and access [3]. With Pilot-PSI the heat transmission factor can be determined and compared with the sheath theory. Experiments with different plasma conditions and gasses are used to expose tungsten targets.

2. Experimental set up

The Pilot-PSI device has been described in detail in [3,4]. The plasma source is a cascaded arc [5], which exhausts into the vessel along the magnetic field axis. To determine the dependence of the sheath heat transfer coefficient on the gas type, experiments are done with argon, nitrogen and hydrogen in high density plasmas with a Gaussian beam profile in both electron temperature and density. Radial profiles of plasma electron density n_e and plasma electron temperature T_e were measured with a Thomson scattering (TS) system 17 mm away from the surface of the target. A detailed description of the use of this diagnostic on Pilot-PSI can be found in [6]. This system can measure n_e and T_e profiles with a spatial resolution of 0.6 mm and an observational error of 3% and 6%, respectively, at $n_e = 4 \times 10^{19}$ m^{-3}. These decrease to 1% and 2%, respectively, at $n_e = 1 \times 10^{21}$ m^{-3}. The flow and temperature of the target cooling water are measured, allowing the total power to the target to be determined by calorimetry. This system is calibrated with a heater with a known power output, the error is 10%. A high speed IR camera (FLIR SC7500-MB) is used to measure the 2D target temperature profile during plasma exposure with a high spatial (0.33 mm) and temporal (200 Hz) resolution. The IR camera is calibrated with a black body and in situ cross checked against a multi-wavelength spectroscopic pyrometer (FAR SpectroPyrometer model FMPI) to account for the role of reflections inside the vessel and the transmission of

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the optical set up. The pyrometer measures a spectrum from 1000 to 1700 nm, with a resolution of 1.56 nm, corrects for the background and detector response and compares the corrected intensity with a black body radiator. After data analysis the output is the intensity per wavelength and the calculated emission spectra and temperature. With this, the emission and/or the transmission of the IR camera can be calibrated. In our case the emissivity (temperature and wavelength dependant) used for the temperature conversion is found in [7], and the transmission determined from the pyrometer is 0.9. This reduces the error in the temperature to 2%.

Tungsten targets of 1 mm thick and 30 mm in diameter are used, clamped onto a water cooled copper heat sink, with grafoil® in between to ensure a good contact surface [8]. The target was kept at a floating potential. The targets are exposed to the plasma for 25 s with a magnetic field of 0.8 T, TS is done after 20 s. In argon slightly higher source settings can be used; 225 A through the arc with a gas flow of 2.4 slm. In hydrogen and nitrogen the source settings are 200 A with 2 slm.

3. Results

With the temperature from the IR camera and the calorimetry, the heat flux can be determined with Ansys. With the T_e and n_e from the TS system, the sheath heat transmission factor γ to the surface can be estimated based on sheath theory [9]. The γ from sheath theory can be compared to the γ calculated with the heat flux from Ansys.

3.1. Sheath heat transmission factor from heat flux calculation with Ansys and TS

The temporal and spatial temperature from the IR camera is used as an input for a 2D axis symmetrical model in Ansys, consisting of a cylindrical tungsten target (($\varnothing$ 30 $\times$ 1 mm), a grafoil layer ($\varnothing$ 22 $\times$ 0.2 mm) and a large copper heat sink ($\varnothing$ 45 $\times$ 80 mm with a cutout in the middle for better water flow). For simplicity the clamping ring that ensures good contact between the target and the heat sink has not been taken into account, but the pressure that is a result of the clamping ring is modeled as contact resistance. The boundary conditions are the temperature on the top surface, emission to the surrounding area, water cooling on the bottom of the copper heat sink and a contact resistance between the different materials. The contact resistance is pressure dependent, and can change with temperature due to different material expansion. The contact resistance results in an impaired heat flow through the model, and thus a different heat flux. This is modeled by two thermal conductance values, in the order of 6000–15,000 W/m^2 K for both layers. Output of the simulation gives the time-resolved heat removed by the water and the time resolved heat flux (q) per calculation cell, see Fig. 1. By changing the contact resistance between the layers, the heat removal through the water in Ansys is adjusted to match the calorimetric results. Although it is unknown what the ratio between the two contact resistances exactly is, the total resistance is what determines the heat flow through the whole model. The introduced error is therefore small, calculations show about 5%.

The sheath heat transmission factor γ can be calculated with $\gamma = q/kT_e\Gamma$, with Γ the particle flux reaching the surface. Γ can be calculated using the Bohm criterion for the sound speed at the sheath entrance; $c_s = [(kT_e + \gamma_s kT_i)/m_i]^{0.5}$ with γ_s the specific heat ratio and m_i the ion mass. In Pilot-PSI the T_i is at least T_e [10], for the following calculations $T_e = T_i$ is used. As T_i is at least T_e a collisional adiabatic plasma is assumed. From fluid models the specific heat ratio is determined at 5/3 [9]. The particle flux than becomes $\Gamma = 0.5\, n_e c_s$ so $\Gamma = 0.5\, n_e(8/3\, kT_e/m_i)^{0.5}$.

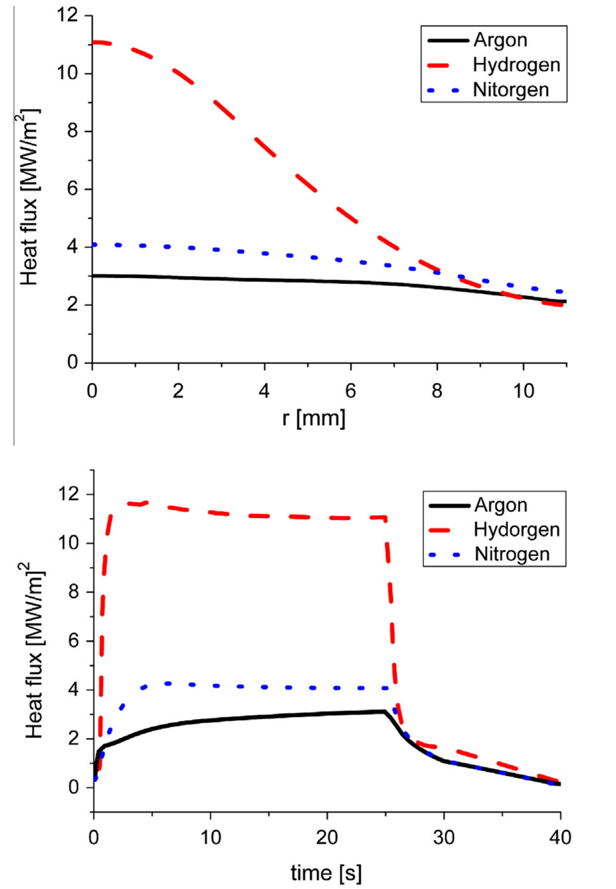

Fig. 1. The heat flux calculated with Ansys from the IR camera temperature and the calorimetry. The upper graph shows the profile at 20 s, the bottom graph shows the maximum heat flux plotted versus time.

3.2. Sheath heat transmission factor based on sheath theory

The T_e and n_e from TS for different gasses are fitted with a Gaussian function and depicted in Fig. 2. For argon the source settings are higher, furthermore argon does not recombine into molecules, so the overall density is higher. The profile of argon is broader due to the higher mass. From these parameters plus the pre-sheath contributions (ε_{preS}), the recombination of ions at the surface (χ_i), association to molecules (χ_r), secondary electron emission (δ_e) and reflection phenomena (R_{iE}, R_{eE}, R_{iN}) [11] the sheath heat transmission factor (γ) can be estimated according to the following equation [9]:

$$\gamma \approx \left(\left[2.5kT_i - 0.5kT_e \ln\left[\left(2\pi\frac{m_e}{m_i}\right)\left(1+\frac{T_i}{T_e}\right)(1-\delta_e)^{-2}\right]\right](1-R_{iE}) + \frac{2kT_e}{1-\delta}(1-R_{eE}) + \varepsilon_{pre} + \xi_i + \xi_r(1-R_{iN})\right)\Big/ kT_e \quad (1)$$

The pre-sheath contribution ε_{pre} = ½kT_e, the energy and particle reflection coefficients are found in [11], but are for 10 eV, as no coefficients are available below that energy and the secondary electron emission yield δ_e for tungsten is computed with

$$\delta_e = 2.72^2 \frac{E}{E_{max}} e^{\left(-2\left(\frac{E}{E_{max}}\right)^{1/2}\right)} \delta_{max} \quad (2)$$

with E_{max} = 650 eV, δ_{max} = 1.4 and $E = -kT_e\, 0.5 \ln[(2\pi\, m_e/m_i)(1 + T_i/T_e)] + 0.7kT_e$.

To estimate the importance of the different factors on the γ, the different components are listed in Table 1, for the maximum