The Control of Convection by Fuelling and Pumping in the JET Pumped Divertor

P J Harbour, P Andrew, D Campbell, S Clement, S Davies,
J Ehrenberg, S K Erents, A Gondhalekar, M Gadeberg, N Gottardi,
M von Hellermann, L Horton, A Loarte, C Lowry, C Maggi,
K McCormick, D O'Brien, R Reichle, G Saibene, R Simonini,
J Spence, M Stamp, D Stork, A Taroni, G Vlases.

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA.

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1 INTRODUCTION

Convection from the scrape-off layer (SOL) to the divertor will control core impurities, if it retains them in a cold, dense, divertor plasma. This implies a high impurity concentration in the divertor, low at its entrance. Particle flux into the divertor entrance, Γ_d, can be varied systematically in JET, using the new fuelling and pumping systems. We estimate the **convection ratio,** Γ_d/Γ_t, where Γ_t is the particle flux to the divertor target, for various conditions of operation. Particle convection into the divertor should increase thermal convection, decreasing thermal conduction, and temperature and density gradients along the magnetic field, hence increasing the frictional force and decreasing the thermal force on impurities.

The **convection ratio,** Γ_d/Γ_t,is estimated as follows ($n_S \approx 2 \times 10^{19}$ m^{-3}), based on EDGE2D [1].

Open configuration (horizontal target)	0.15	0.35
Closed configuration (vertical target)	0.03	0.19
Typical conditions	Low pumping/wall pumping and/or fuelling in divertor	High pumping/wall pumping & fuelling in torus

The limited range is due to ionisation in the divertor. The configuration is more "open" at low density and with hydrogen, giving higher Mach number at the divertor entrance.

The control of convection is important, so is studied in JET, using the new fuelling system. We discuss a limited study, using the Mk I Divertor, with horizontal target, and no pumping. It is expected that the control of impurities may be sensitive to small changes in Mach number, $-0.1 \leq M \leq 0.1$, say. The study of fuelling is supported by modelling with EDGE2D, as described in Sections 5,6.

2 THE EXPERIMENT IN JET AND THE MODEL PLASMA FOR EDGE2D

Fuelling ("puff" in Figures) is now provided at three poloidal locations in JET (Fig 1a), top (thick SOL), outer midplane, OMP (thin SOL, hence deeper penetration), and in the divertor, just below the X-point. The divertor system has 24 toroidally distributed inlet pipes, controllable in quadrants (six pipes each), via four independent fast gas valves. Pumping will be via a cryopump, stronger in the outer divertor, but not yet available, so we use wall-pumping in this study. Wall-pumping is assumed to occur mainly in the divertor and is found to decrease in strength throughout the day, from ~ $4 \times 10^{21} s^{-1}$ to ~ $2 \times 10^{21} s^{-1}$ in high density Ohmic discharges. The plasma configuration studied is shown in Fig 1a and the model geometry in Fig 1b. Fuelling in EDGE2D is simulated by introducing D atoms ($T \approx 0.1$eV) at the walls where indicated, while pumping is simulated by absorbing 10% of the flux of neutrals onto the divertor walls. Steady state is achieved by matching the fuelling rate to the wall pumping rate found in experiment and model respectively.

3 EXPERIMENTAL PROCEDURE

An Ohmic density scan was made in a series of discharges (2.8T, 2MA), with deuterium fuelling in the divertor (1,2 or 4 quadrants). Several discharges had top or OMP fuelling for comparison. The total electron content, N, increased until fairly constant. The pumping rate, ϕ_{pump}, is given by

$$\phi_{pump} = \phi_{fuel} - dN/dt \qquad (1),$$

and in every discharge $|dN/dt| \ll \phi_{pump}, \phi_{fuel}$ during the ≈ constant density phase. On the first day, with purely Ohmic discharges (#29756-66), data were taken at $t_{data} = 14 - 16s$. On the second day (#29810-23), $t_{data} = 13.5s$, avoiding the NBI commissioning time ($t_{NBI} \geq 16s$; $P_{NBI} \leq 12\,MW$).

4 EXPERIMENTAL RESULTS

Figure 2 shows the density scan. The specific pumping rate, ϕ_{pump}/N(Fig 2a), lies mostly between 1 s^{-1} and 3.3 s^{-1}. Considering the pumping observations sequentially, there was first a density limit pulse

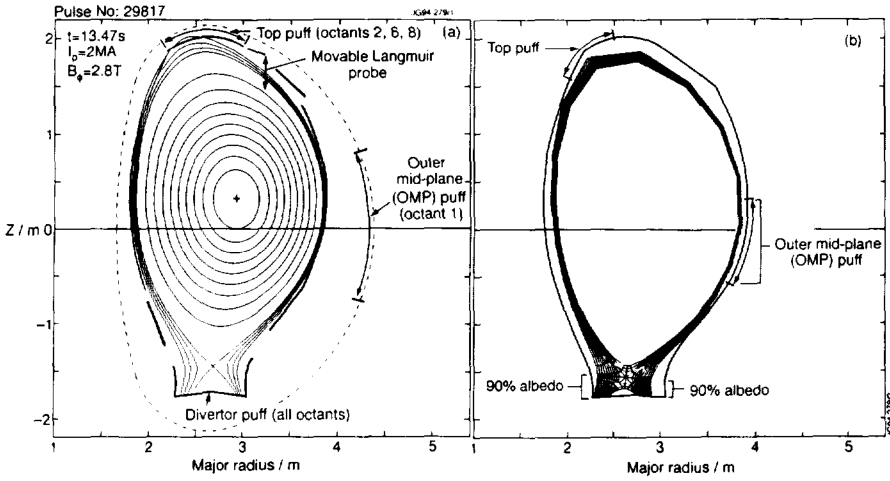

*Figure 1: The geometric configuration, with fuelling locations of **a)** the experiment in JET, and **b)** the model plasma used in EDGE2D.*

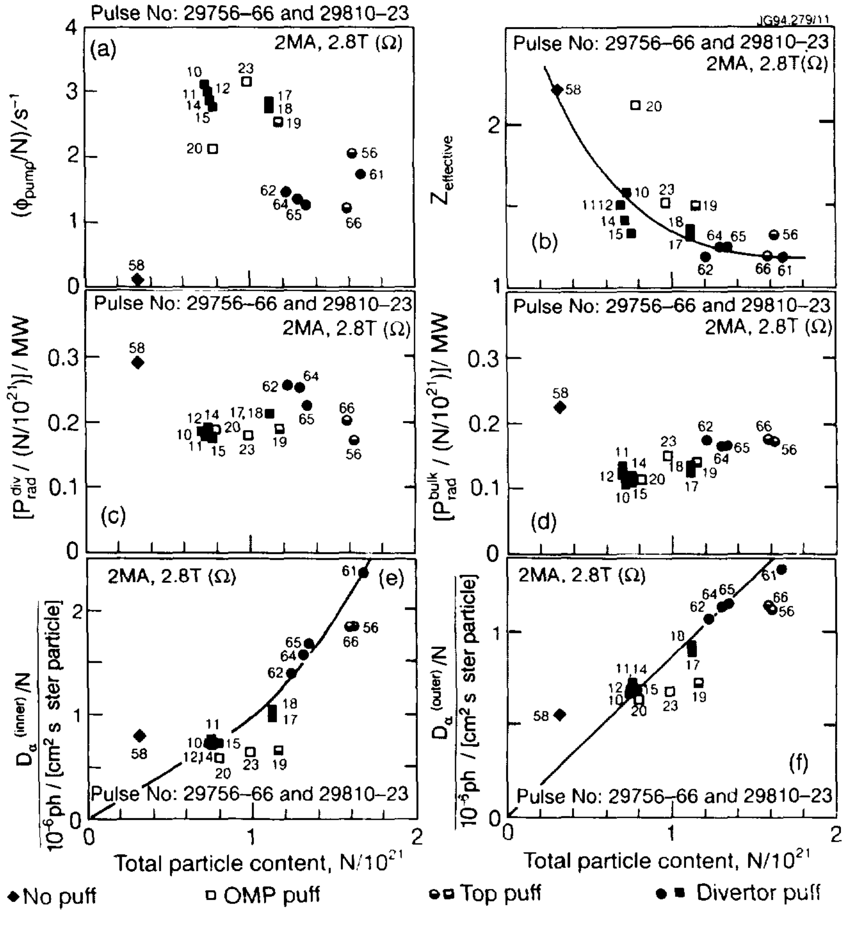

*Figure 2: The density (total electron content, N) scaling of **a)** the specific wall-pumping rate, Φ_{pump}/N (see Equ. 1), **b)** the global $Z_{effective}$ **c,d)** radiation power in divertor and bulk plasma (power/particle is plotted), and **e,f)** D_α intensity in inner and outer divertors (radiation intensity per particle is plotted). Solid symbols represent fuelling in the divertor; open/half-solid symbols represent SOL fuelling. With SOL fuelling we see higher $Z_{effective}$ and lower divertor radiation (total and D_α) but no change in bulk plasma radiation or in wall pumping.*

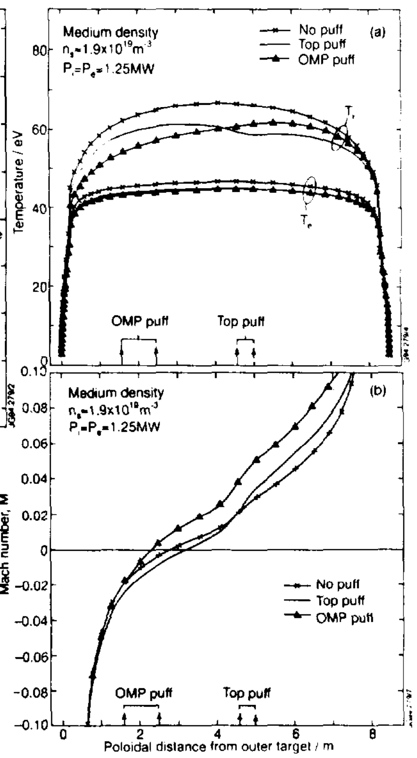

*Figure 3: Poloidal profiles on the separatrix, fuelling as shown: **a)** T_i, T_e, **b)** Mach number along the separatrix.*

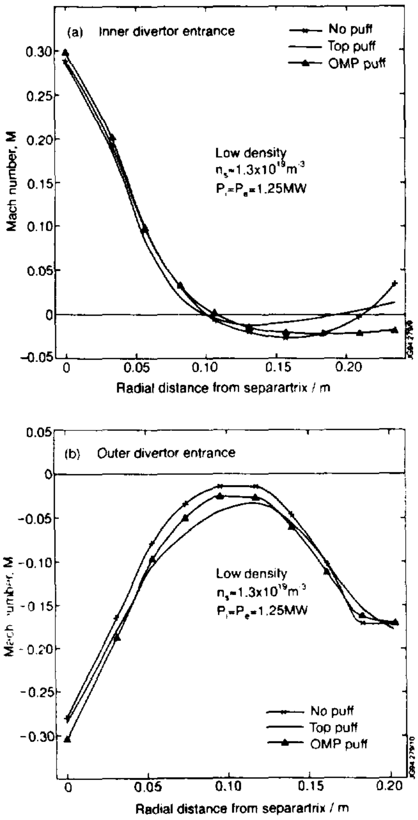

*Figure 4 Mach number of the plasma outside the divertor entrance, against radial distance from the separatrix, **a)** inner divertor entrance, **b)** outer entrance.*

(297**56**) with top fuelling, then a low density pulse (fuelling off), where ϕ_{pump}/N was much lower. Divertor fuelling was used in **61**, which showed 20% less pumping than **56**, and the specific pumping rate continued to fall throughout the sequence **62-65**, with divertor fuelling, and **66**, with top fuelling. There seems little to distinguish the pumping in these Ohmic discharges, with top or divertor fuelling. On the second day, ϕ_{pump}/N was almost twice as large (only partly due to the timing of the observation, 1.5 s earlier). Again the specific pumping rate fell, the sequence 298**10-15** showing this clearly. The trend was resumed during **17,18** & **19**, the latter with top fuelling, and if we allow for the density variation there is nothing to suggest that **19** (top fuelling) or **20** (OMP fuelling) lie outside the sequence. In contrast, **23** (OMP fuelling) has at least 50% more pumping than expected. The specific pumping rate falls by 3% to 10% per discharge, increasing with plasma density as expected under high recycling conditions. A regression fit to the data in Fig.2a shows that ϕ_{pump} varies approximately as $N^{1.3}$ and that it increased by a factor greater than two on the second day. All measured values of ϕ_{pump} lay within about 10% of the regression line (apart from #298**23**) and, for those observations with fuelling in the main SOL, the deviations from the regression fit were random in sign as well as being of similar magnitude to those with divertor fuelling. This confirms the analysis of data given above.

The global $Z_{effective}$ varies with density as usual, but is higher for four of the five plasmas with SOL fuelling (Fig2b). This implies greater carbon content, due either to sputtering at the fuelling location or increased sputtering and escape of carbon from the divertor. In contrast, the bulk radiation is not affected fuelling location (Fig2d): either it is dominated by high Z species (e.g. Cl), little affected by changes at the edge, or we have an inconsistency. However the trends do appear to be significant.

Radiation in the divertor shows consistent trends in line with expectations. With divertor fuelling, the D_α intensity at both targets increases rapidly with N, D_α/N increasing linearly with N up to $N=10^{21}$, with about 10% greater intensity in the inner divertor. Above $N=10^{21}$ the increase, still linear in the outer diveretor, is faster than linear in the inner, indicating a cold plasma. The D_α intensity is up to 25% lower with fuelling in the SOL (Fig.2e,f). There is a similar trend in the total divertor radiation obtained bolometrically (Fig 2c).

Overall, there is clear evidence (D_α /bolometry) that particle fluxes in the divertor increase with density ($D_\alpha \sim N^2$ or more) as well as with divertor fuelling. Also the specific pumping rate increases with density ($\phi_{pump} \sim N^{1.3}$), but at a lower rate than the increase in particle fluxes in the divertor. It is surprising that the specific pumping rate is not increased by fuelling in the divertor, when fluxes are higher. Can it be that pumping occurs near the fuel inlet, possibly due to charge exchange?

SOL profiles, measured with a movable Langmuir probe in discharges 298**10-20**, showed a fairly constant narrow layer. In 298**19** (top fuelling) the scrape-off thickness increased substantially compared to 298**18** with divertor fuelling, (λ_n, 13.7→21mm; λ_Γ, 8.8→14mm; λ_T, 23→27mm). We expect broadening with fuelling in the SOL, especially at the top of the vessel, which would exaggerate differences between torus and divertor fuelling. No significant difference is apparent in Fig.2 for discharge 298**19.** Plasma profiles at the target were unavailable in these discharges.

5 MODELING WITH EDGE2D: PROCEDURE

Nine steady state runs with EDGE2D and NIMBUS were performed $P_i^{SOL}=P_e^{SOL}=1.25MW$; $D_\perp=0.2$ m^{2}s^{-1}, $\chi_\perp=1.5$ m^{2}s^{-1}; L-mode values), with three densities and three fuelling assumptions: top or outer mid-plane (OMP) fuelling and no fuelling (≈divertor fuelling). The plasma geometry is similar to that used experimentally (Fig 1). The interaction between plasma and walls in the torus was minimised, so that changes due to changing fuelling point would be detectable. To this end, a diffusive flux boundary condition with shallow gradient (λ_n=3cm) was set at the outer surface of the plasma region used in EDGE2D (Fig.1b). Plasma crossing this outer surface was recycled at the divertor target. About half of the recycling was of this type, the other half flowing to the target via the model plasma region (Fig.1b). This outer boundary condition produced relatively flat radial density profiles in the SOL, so, although the average density simulates experimental results, details of density profiles do not. The temperature profiles are consistent with typical observations, however.

6 MODELLING WITH EDGE2D: RESULTS AND DISCUSSION

Total plasma flow to the targets, Γ_t, is tabulated below, with other flows of interest. The prescribed wall pumping removes up to 8% of the target flow, which is then re-injected as fuel. Pumping and fuelling has a predictably small effect on parameters in the SOL and divertor channel. At all three densities, T_i is reduced (more so at the fuelling point) by ~5eV at the separatrix, and T_e fell by 1 to 2eV (Fig.3a). Although impurities were not studied, the dip in T_i implies the thermal force on impurity ions is directed from the fuelling point towards the divertor. Frictional forces increase due to reduced T_i and to flow induced by fuelling. Mach number profiles (Fig.3b) show SOL fuelling moves the stagnation point in the SOL towards the fuelling point from its location with no fuel, and increases the gradient of M.

	No fuelling			**Top fuelling**			**OMP fuelling**		
Albedo in divertor	100%			90%			90%		
Edge density/$10^{19}m^{-3}$	2.45	1.84	1.31	2.50	1.91	1.32	2.67	2.04	1.41
Flow to target, $\Gamma_t/10^{21}s^{-1}$	202	202	197	210	210	201	208	210	200
Fuel/pump flow/$10^{21}s^{-1}$	0	0	0	16.2	13.2	10.1	16.3	12.7	9.6
Flow into divertor/$10^{21}s^{-1}$	54.9	47.3	36.8	58.8	48.4	38.8	60.2	50.7	38.2

Edge plasma densities and global flows obtained in simulations of fuelling and pumping with EDGE2D/NIMBUS.

SOL fuelling had little influence on ***separatrix*** Mach number at the divertor entrance, radial profiles (Fig.4) showing strong flow ($M \approx 0.3$) into each divertor. The outer part of the profile shows a tendency to flow reversal, reduced by SOL fuelling. Detailed study shows flow reversal at/or near each divertor entrance, only in the outer part of the profile. SOL fuelling diminishes the flow reversal zone and increases plasma density away from the separatrix. Fuelled neutrals are attenuated within a few mm. Those surviving, having charge-exchanged, penetrate easily, especially at the outer mid-plane.

7. SUMMARY AND CONCLUSIONS

Changes in convection in the SOL, caused by gaseous fuelling, have been studied, both experimentally in the JET Mk I divertor, and with EDGE2D/NIMBUS. In Ohmic plasmas (2MA, 2.8T), divertor fuelling gave low $Z_{effective}$ with increased radiation intensity (D_α/bolometry) in the divertor. Fuelling in the main SOL gave higher $Z_{effective}$ but not bulk radiation, and decreased radiation in the divertor. The wall-pumping speed varied day by day by at least a factor of two. On a given day, $\phi_{pump} \sim N^{1.3}$. and $D_\alpha \sim N^2$ (or more). Despite extra fluxes with divertor fuelling, there was no increase in wall-pumping speed, suggesting that pumping may occur at the fuelling point. Preliminary measurements with a movable Langmuir probe show a thicker SOL with top fuelling, in qualitative agreement with EDGE2D. One aim of the experiment was to investigate the need for toroidally uniform fuelling. Preliminary results, though unclear, help to define a future investigation. The experiment described was part of a larger study, to include controlled pumping with a cryo-pump. When commissioned, it will be possible to test whether wall-pumping occurs at the fuelling point. With EDGE2D, a 90% albedo on the divertor side-plates pumped ≤8% of the target plasma flow. Fuelling in the main SOL reduced T_i, with a minimum near the fuelling point. This suggests fuelling in the SOL might control impurities, via frictional and thermal forces. In contrast, increased impurity content was found in JET, using the Bremsstrahlung measurements, but not the bolometry. Impurities generated at the fuelling point might be implicated here, further work being needed. EDGE2D showed that fuelling alters profiles at the divertor throat, flow reversal regions being diminished if not removed. Although details may be model dependent, the sensitivity to fuelling procedure implies that a versatile fuelling system such as now installed in JET, is needed to optimise performance.

[1] R Simonini, G Corrigan, J Spence, A Taroni and G Vlases, 20th EPS, Lisbon, 26-30 July 1993.