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ABSTRACT

Many theoretical models have been proposed in the literature to explain the observed anomalous transport of energy in tokamaks. High quality data on experimental diffusivities for ion and electron thermal transport from JET is used to assess the value of a large number of the models. Particular emphasis is placed on using only data that satisfies the appropriate validity conditions for the various models.

1. INTRODUCTION

In order to assess the energy confinement capability of a tokamak design it is necessary to develop models for the observed anomalous ion and electron thermal diffusivities χ_i and χ_e, respectively. These models may be based on semi-empirical modelling (e.g. the Rebut-Lallia-Watkins model) or deduced from the turbulent transport arising from the non-linearly saturated stated of various micro-instabilities. Given the variety of instabilities present in tokamaks and the different non-linear calculations that are employed, a large number of turbulent diffusivities exist in the literature. Their relevance is often judged by their success in producing the observed confinement time scaling laws. A far more demanding test is whether they can reproduce the same radial profiles as those observed experimentally. High quality local power balance data is required to determine these profiles. The JET database can provide this information for a large number of shoots and a wide variety of discharge types (Ohmic, L-mode, H-mode,.....) and offers a valuable opportunity for carrying out tests of theoretical models. We have embarked on a systematic programme of assembling a theoretical database of χ_i and χ_e from the literature, with particular emphasis placed on ascertaining their regime of validity, and testing them against JET data in situations that satisfy these various validity conditions [1, 2]. In section 2 we report on tests of recent χ_i models; in section 3 we consider tests of χ_e models. Of course, as the inadequacies of models emerge through testing against experimental data, new ingredients are incorporated in the models to remedy these weaknesses. Thus in the respective sections we briefly discuss some recent developments in the literature and draw some conclusions. However the testing programme outlined here needs to be ongoing and new models should be assessed in a similar way.

2. ION THERMAL DIFFUSIVITIES

2.1 Data

The discharges considered involve a large number of limiter L-mode shots but several H-mode shots with a magnetic separatrix and a small number of high performance regimes of special interest, such as the PEP mode and hot-ion H-mode, are also included. Only discharges is approximate steady state are considered. Transport in the hot core $\rho = r/a < 0.4$ is obtained using sawteeth free discharges. Here $T_i(\rho)$ is not known directly so that $\chi_{eff} = -q_{cond}/n(\nabla T_i + \nabla T_e)$, (with models for $T_i(\rho)$) is then used instead of χ_i. In the outer region $\rho \geq 0.5$, the most important for confinement, only data with measurements of $T_i(\rho)$ and an error in χ_i not larger than $\pm$ 50% is employed. When comparing with specific theoretical models for χ_i only data satisfying the appropriate instability and validity conditions are selected; this can often restrict the data available to narrow radial zones.

2.2 Theoretical Models

A range of models for χ_i based ∇T_i driven turbulence (η_i-modes and Trapped Ion modes) appearing in the literature over recent years have been considered - some other more recent models are discussed briefly in section 2.4. In the case of η_i-mode models only the toroidal models are appropriate for JET since generally $L_s > R/2$ where L_s is the shear length. All the models considered are of the Gyro-Bohm type.

$$\chi_i \sim \frac{\rho_s^2 c_s}{R} F(\upsilon_*, q, s, \beta, ...) \tag{1}$$

and can be found in the following references:

η_i-Modes

Biglari, H. Diamond, P.H. and Rosenbluth, M.N. Phys. Fluids B1, 1990, 1989; Romanelli, F. Phys. Fluids **B1**, 1018, 1989; Guo, S. C. et al., Plas. Phys. Cont. Fus. **31**, 423, 1989; Hong, B.G. and Horton,W. Phys. Fluids **B2**, 979 1990; Dominguez, R.R. and Waltz, R.E. Nucl Fus. **29**, 885, 1989; Romanelli, F. Chen, L. and Briguglio, S. Phys. Fluids **B3**, 2496, 1991; Kim, Y.B. et al., Phys. Fluids B3, 384, 1991.

Trapped Ion Modes

Diamond, P.H. and Biglari, H. Phys. Rev. Lett. **65**, 2865, 1990; Biglari, H. Diamond, P.H. and Rosenbluth, M.H. Phys. Fluids **B1**, 1990, 1989; Xu, X. Q. and Rosenbluth, M.N. Phys Fluids B3, 1807, 1991; Garbet, X. et al., Phys Fluids B4, 136, 1992.

2.3 Comparisons

Sufficient data satisfying the validity criteria for each model is available to provide a satisfactory test. They are all found to share a common failing - they exhibit the wrong radial profiles for χ_i. In other words the radial temperature profile factor $\sim T^{3/2}$ in equation (1) cannot be offset by the radial dependencies in the functions F - indeed they often exacerbate the situation due to inverse dependencies of the ν_* and s. This can be quantified in terms of the Pearson coefficient, which takes the values +1 (-1) if experimental and theoretical profiles perfectly correlate (anti-correlate) and zero if there is no detectable correlation. No model exceeds a value + 0.1 and many are negative. According to most of the stability criteria the hot plasma core of sawteeth-free discharges is unstable with respect to ∇T_i driven modes and the corresponding χ_i should be much larger than measured. This would have prevented the achievement of the high central temperatures observed in the PTE experiment and PEP shots. Conversely the theoretically predicted transport tends to vanish towards the edge, either because the instability threshold is not exceeded or χ_i is small - again in contrast with observations.

2.4 Discussion

The models tested do not provide a satisfactory description of JET. However, some of their weaknesses in describing radial profiles have already been identified in comparisons with other devices and modifications or new models have been introduced to address these problems. Examples that have had some success on TFTR are those due to Horton et al., [3] and Weiland and Nordman [4]. Hua et al., [5] have modelled DIII-D with a modified expression for the critical ∇T_i and Guo and Romanelli [6] have also provided a comprehensive analysis for the critical gradient. Beklemishev and Horton [7] have introduced the idea of the 'density of states' (which awaits confirmation by non-linear calculations).

Following the work of Connor et al., [8] on extended radial structures for toroidal drift waves, Romanelli and Zonca [9] have shown that the turbulent correlation length (and hence χ_i) is a sensitive function of s and would lead to better profiles. All these ideas and models should be tested against the JET data.

3 ELECTRON THERMAL DIFFUSIVITIES

3.1 Data

The data is again taken from radial scans of a set of approximately 100 sawteeth-free (mostly L-mode) discharges at various levels of plasma current, density, toroidal magnetic field and auxiliary input power. Generally only χ_{eff} is available and a basic assumption is that this should reflect the properties of χ_e.

3.2 Theoretical Models

Many more models for χ_e than for χ_i are available (details of those considered are in Reference [2]). They can be classified into those due to (i) electron drift waves driven by circulating or trapped particle responses, in collisionless and collisional regimes with slab-like or toroidal mode structures and calculated using a variety of non-linear saturation mechanisms (16 models); (ii) quasi-linear and stochastic transport caused by electromagnetic fluctuations on the Larmor radius and collisionless skin depth scale and transport from η_e (or ∇T_e) modes (12 models); (iii) convective or stochastic magnetic field transport caused by 'resistive' fluid turbulence driven by pressure gradients, in collisional and collisionless regimes, and by resistivity gradients (12 models); and (iv) transport due to non-linearly unstable magnetic islands caused by bootstrap currents, finite ion Larmor radius etc. (8 models; the Rebut-Lallia-Watkins model has been considered elsewhere and is not included here).

3.3 Comparisons

For relevant or promising models, comparisons of the radial profile of χ_e (r) for a typical L-mode shot were made and then, at a fixed radius, scans over a set of shots with different densities, or auxiliary power or current were carried out.

For the electron drift wave models (i) radial profiles and scalings of χ_e are unsatisfactory The best models are those due to Hirshman and Molvig (Phys.

Rev. Lett. **42**, 648, 1979) and Kaw (Phys. Lett. **90A**, 290, 1982). A number of the models (ii) show more promise - e.g. a suitable 'mix of ingredients' is present in that due to Zhang and Mahajan (Comments on Plas. Phys. Cont. Fus. **11**, 243, 1988). The best of the class of models in (iii) are those discussed by Connor (Plas. Phys. Cntr. Fus. **35**, 757, 1993). Although the radial profile of χ_e reduces to the outside somewhat in contrast to the experiment, scalings with current density and power are encouraging. Similar comments apply to the best of the models in category (iv), namely that due to Kadomtsev (Nucl. Fus. **31**, 1301, 1991), although it does not predict the current density scaling.

3.4 Discussion

The better radial profiles for χ_e and scalings with plasma density are obtained with those models based on quasi-linear and stochastic transport of electrons in a spectrum of electromagnetic waves involving wavelengths comparable with the collisionless skin depth. They do not give an entirely satisfactory representation of power degradation; this can be achieved if they are combined with transport due to turbulence at the ion Larmor radius wavelength. Models involving pressure driven instabilities lead to the correct current scalings, however they do not always recover the favourable dependence on plasma density which is a characteristic of JET L-mode thermal energy confinement scaling. Drift wave turbulence can yield the correct power degradation but suffers from the same problems with radial profiles as the χ_i models. Further inverse factors of L_n are helpful but, since these tend to be correlated with density, would predict too strong a favourable density dependence in JET. Factors of q, which would improve current scalings, and inverse factors of L_T would have more desirable results.

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