Numerical simulations for hydrodynamic technique protecting optical components in ITER divertor

I M Bukreev¹, E E Mukhin¹, S V Bulovich², A A Matyushenko², N A Babinov¹, A M Dmitriev¹, A E Litvinov¹, A G Razdobarin¹, D S Samsonov¹, L A Varshavchik¹ and P A Zatilkin¹

¹Ioffe Physical-Technical Institute, 194021, 26 Politekhnicheskaya, St.Petersburg, Russian Federation
²Peter the Great St.Petersburg Polytechnic University, 195251, 29 Politekhnicheskaya, St.Petersburg, Russian Federation

e-mail: bukreev.i.m@mail.ioffe.ru

Abstract. There are several protecting techniques managing with contamination on optical surfaces of in-vessel diagnostic components in ITER. Analysis of impurity transport in narrow and curved gaps gave us the idea that it can’t be explained by convection flows. The proposed protecting construction, situated between plasma and irradiating laser mirror launcher, was analysed for effectiveness. The protecting ability of this construction is based on the principles of hydrodynamic, in particular on bevelled entrance, which provides redirection of polluting gas flow away from the optical components due to angling optical and geometrical channel axes. Several different numerical simulations were studied. The design, setting objectives as well as equations and parameters are under discussion. Results of 2D and 3D numerical simulations are provided.

1. Introduction

Design of in-vessel diagnostic components is one of the challenging engineering and research areas of future fusion industry. In particular, the International Thermonuclear Experimental Reactor (ITER) should be put into operation by 2025 to develop technologies and processes needed for fusion power plant. Therefore, a lot of related research is underway now, including development of plasma diagnostics required for monitoring the high-temperature plasma parameters and first wall components. The tokamak first wall integrity is the most critical problem for divertor (a specific area of the tokamak volume), where the outer layers of plasma are guided by magnetic field of a special shape providing heat flux 5 – 30 MW/m². Existing materials and heat removal systems can withstand no more than ~10 MW/m² of stationary energy fluxes. Otherwise, serious accidents may occur. Therefore, the divertor plasma parameters determined by inward energy fluxes should be monitored and controlled to avoid the reactor malfunction. Divertor Thomson scattering – one of the key diagnostics of ITER divertor – is a laser-aided plasma diagnostic using special laser launcher located close to the plasma sputtered first wall. Optical components near the first wall surfaces can be exposed to materials eroded from plasma facing components, mainly beryllium and probably tungsten. In ITER divertor ports, the contamination rates are foreseen to be more intensive than in equatorial and upper ports. Thus, a special attention should be paid to protection of optical components located in the divertor region.

Several methods are considered to manage with contamination on in-vessel optical components, including laser cleaning, plasma cleaning and gas puffing in the vicinity of protected areas. The gas-counter-flow technique requires intensive gas puffing incompatible with ITER pumping capacity. Transport of the materials eroded from first wall of tokamaks is poorly investigated. In the most advanced modern tokamak JET ILW (with ITER-like first wall), the eroded materials were found in narrow and curved gaps away from the first wall [1]. We propose to explain the behavior of the eroded materials by a
gas expansion transport or by convection during short pressure jumps after transient events such as events called edge-localized modes (ELMs) [2]. The pulsed-pressure deposition mechanism was proposed basing on the research of convection currents in ASDEX [3, 4]. Due to the complex filamentary nature of ELM events observed in all modern tokamaks [5], plasma pressure fluctuations in divertor have a complex three-dimensional (toroidally asymmetric) structure. The time scales of the ELM heat load in the divertor were intensively studied by work from ASDEX Upgrade, MAST and JET [6]. Latter studies conclude that the rise time of the ELM heat pulse will be $\tau_{\text{rise}} \sim 0.25$ ms in the ITER burning plasma scenario. An example of the two-dimensional numerical simulation of $T_e$ and $n_e$ (at the ELM peak) distributed along the outer leg of ITER divertor [7] predicts pressure fluctuations in ITER divertor from 10 to 100-1000 Pa with duration of $\sim 0.3-1$ ms and average frequency repetition of tens of Hz. Large duty cycles of the pressure fluctuation make it possible to consider each ELM incident as independent. The potential importance of high fluxes on ITER plasma-facing components stimulated more detailed investigation of the observations at ASDEX Upgrade [8]. The neutral fluxes measured in this work by in-vessel pressure gauges located on the back of the divertor targets reached $4 \times 10^{23}$ deuterium/m$^2$/s and more. Assuming room temperature velocities of the deuterium atom gas flows, this flux corresponds to the flow pressure fluctuations of $\sim 2.6$ Pa and higher (assuming $D_2$ gas, the flow pressure is $\sim 3.7$ Pa). The pressure fluctuation can be even more taking into account that the measured pressure values were at the upper detected limit, since the sensors provide pressure measurement in a range of $10^{-3} - 5$ Pa [9, 10]. The time response of the gauge is typically $\sim 2$ ms, but the response time of the volume and conductance was estimated as high as $\sim 6$ ms [11]. Assuming 0.3 ms ELM duration, the neutral pressure jump of a few Pa measured behind the divertor plates, can be recalculated to tens of Pa pressure jump on the first wall of ASDEX Upgrade worked in ITER baseline scenario.

To protect two laser windows used for launching laser radiation into the divertor plasma, we propose using special box situated in 2 cm gap between the divertor cassettes. The principle of the protection is based on deviation of the hydrodynamic flow away from the optical axis and absorption/pumping provided by diffusion transferring Be atoms to the box walls. Thus, the bulk of the gas flow bypassed the optical components without blocking direct view of the outer leg divertor plasma. The scheme of the assembly is shown in Figure 1.

Figure 1. Scheme of the special box situated in 2 cm gap between the divertor cassettes.

2. Setting objectives
At the first stage, dynamic characteristics of pressure and velocity fields of the gas flow with turbulent wakes were investigated numerically within two-dimensional (2D) approximation. Approximating a 3D impurity transfer analysis of a gas flow via a 2D cross-sectional analysis introduces errors in the computed distribution of deposits. Thus, the final design effectiveness was assessed in 3D mesh. The data on dynamic behavior of polluting flows were obtained from pressure and velocity fields to predict distribution of the pollution deposits. When finalizing the assembly design, a number of additional 2D calculations were performed for channels of varied geometry to minimize design-related pollution near protected area.
To check effectiveness of the protecting box in the gap between two neighboring divertor cassettes, the numerical experiment was performed in approximation of a continuum model using FVM (finite volume method) VOF (volume-of-fluid) ANSYS/FLUENT computational code [12] for the Navier-Stokes equations:

- **Continuity equation**: \( \frac{\partial \rho}{\partial t} + \nabla (\rho \vec{V}) = 0 \) (1)

- **Momentum equation**: \( \frac{\partial}{\partial t}(\rho \vec{V}) = \nabla (\mu \tilde{S}) - \nabla (p + \frac{2}{3} \mu \nabla \vec{V}) \) (2)

- **Energy equation**: \( \frac{\partial}{\partial t}(\rho C_v T + \frac{\rho \vec{V}^2}{2}) = \nabla (PV) + \nabla (\lambda VT) \) (3)

- **General gas equation**: \( pV = \frac{m}{M}RT \) (4)

Mass concentration balance equation (Be) \( \frac{\partial c}{\partial t} + \nabla (I_{Be}) = 0 \) (5)

where \( \vec{V} \) – velocity vector; \( p, \rho, T, V \) – pressure, density, temperature and gas volume; \( \tilde{S} \) – strain tensor; \( C_v \) – specific heat at constant volume; \( \lambda \) and \( \mu \) – coefficients of thermal conductivity and dynamic viscosity; \( R \) – universal gas constant; \( P \) – stress tensor; \( m \) and \( M \) – gas mass and molar mass; \( I_{Be} \) – specific mass flow; \( c_{Be} \) – Be mass concentration.

The thickness of deposited films on the surfaces was estimated as a time integral of the substance \( (Be) \) flow on the wall:

\[
H = \int_{0}^{1} \rho D \vec{V} d\tau
\]

where \( \tau \) is the total pressure jump duration, \( D \) – diffusion coefficient, and \( \rho \) – flow density.

The continuum model was implemented using the Lennard-Jones approximation: a simple pairwise interaction model of non-polar molecules, in which interaction energy between two particles is a function of a distance between them: \( U(r) = 4\epsilon \left[ \left( \frac{\sigma}{r} \right)^{12} - \left( \frac{\sigma}{r} \right)^{6} \right] \), where \( \epsilon \) – depth of potential well; \( \sigma \) – distance where the interaction potential is 0; \( r \) – distance between the molecules [13]. Applying continuum model for this particular problem requires certain assumptions. The main criterion of the continuum model assumption is the degree of gas rarefaction categorized normally by the Knudsen number \( (Kn) \) defined as the ratio of mean free path of gas molecules to characteristic flow length (here the gap between neighboring divertor cassettes). This number in a fusion device covers values starting from the slip regime \( (10^{-3} < Kn < 0.1) \) above the dome and close to the divertor targets and the transitional \( (0.1 < Kn < 10) \) or even the free molecular \( (Kn \rightarrow \infty, \text{collisionless}) \) regimes in the sub-divertor area and inside the vacuum pumps. At initial stage of the gas expansion into the protecting box volume, the background pressure \( \sim 10 \) Pa corresponds to \( Kn \sim 10^{-1} \) (mean free pass of \( \sim 0.1 \) cm and the box width of \( \sim 2 \) cm); hence, the continuum model is an estimation only. As the flow expands, velocity smoothly decreases, while pressure increases up to \( \sim 100 \) Pa; then, the continuum model approximation becomes reasonable \( (Kn \sim 10^{-2}) \) [14].

The computational domain and the boundary conditions are presented in Figure 2. Surfaces in front of the mirror components are open (pressure outlet), the output windows for the laser radiation are located at a distance of \( \sim \) their linear size from the assembly under consideration. The boundary conditions taken for the calculations are as follows:

- Pressure and temperature behaviour (as a function of time) at the inlet to the computational domain (inlet):
  \[
  P(t) = P_m \sin(\frac{\pi t}{\tau})
  \]
  \[
  T(t) = T_m \sin(\frac{\pi t}{\tau})
  \]
  where \( P_m \) and \( T_m \) – maximum pressure and temperature during
the ELM incident, 100 Pa and 300 K; \( \tau \) – pressure jump duration 0.35 ms; concentration \( c_{\text{inlet}} = 0.01 \) (1% Be).

- Zero mass of the impurity component on all solid surfaces (walls): \( c_{\text{w}} = 0 \); zero heat flux values.
- Free boundary in terms of pressure: \( p_{\text{outlet}} = 10 \) Pa at the output face of the computational domain (pressure outlet).

To save computational resources and time, the computational domain for 3D calculation was assumed to be symmetric relative to the gap walls. Thus, calculations were performed in a half of the simulated space.

Simulation mesh has of \( \sim 4 \times 10^6 \) elements and nodes with increased density of elements near the edges of the computational domain to better resolve the boundary layers (see Figure 3).

The monitoring points were placed in front of the mirrors. Throughout the calculations, deposition flows \( pDc \) were monitored to calculate the thickness \( H \) of the films deposited on the protected mirror.

Transfer coefficients were determined via molecular kinetic theory for two-component environment: the background gas \( D_2 \) (marked as 1) and \( Be \) as a pollutant (marked as 2). The diffusion coefficient was estimated as follows [15]:

\[
D = 0.0026228 \cdot (T^4 (M_1 + M_2) / 2M_1M_2)^{1/2} \cdot (\sigma_{12} \Omega_{12}^{(1,1)}(T^*)^{-1})
\]

Figure 2. Computational domain and boundary conditions.

Figure 3. Simulation mesh.

where \( T \) – temperature, \( p \) – pressure, \( M_1 \) and \( M_2 \) – molecular masses of diffusing gases (in our case, masses of two components), \( \sigma_{12} = \frac{1}{2}(\sigma_1 + \sigma_2) \), \( \Omega_{12}^{(1,1)}(T^*) \) – the first collision integral – tabulated in [16].

Calculations were made assuming 1% of \( Be \). The parameters used for calculation of the diffusion coefficient are as follows [15]:
Table 1. Lennard-Jones model parameters.

| Parameter                              | \( Be(g) \) | \( D_2 \) |
|----------------------------------------|-------------|------------|
| Molecular mass, mol. a.e.m.            | 9           | 4          |
| Specific heat, J/kg·K                  | 2311        | 7250       |
| Dynamic viscosity, \( \eta, \text{Pa} \cdot \text{s} \) | \( 0.5 \cdot 10^{-5} \) | \( 1.2 \cdot 10^{-5} \) |
| Characteristic energy, \( \varepsilon/k, K \) | 3000        | 40         |
| Distance where inter-particle potential is zero | 4           | 3          |

In the table 1 dynamic viscosity is determined from the following equation:

\[ \eta = 2.7 \cdot 10^{-2} (M \cdot T)^{1/2} (\sigma^2 \Omega^{1.25} (T^*)^{3})^{-1} \]

where \( \Omega^{1.25} = 1.157 \cdot T^{0.1472} \) is momentum transfer collision integral (second collision integral, showing deviation from the model with gas molecules as elastic moving balls); \( M \) – molecular mass, \( T \) – molecular temperature, \( T^* = T(\varepsilon/k)^{-1} \) – characteristic temperature, \( \varepsilon/k \) – characteristic energy, where \( \varepsilon \) – molecular energy, \( k \) – Boltzmann constant, is determined from the equation:

\[ \varepsilon/k = 1.18 \cdot T_{\text{boil}} \]

\( T_{\text{boil}} \) – boiling temperature.

As discussed earlier the main task was to prevent penetration of the pollutant flow into the area of optical components, while maintaining the direct view of the plasma. At first, we proposed [1] to slow down gas flow by diaphragms installed along the flow path. However, the resulting deceleration was not enough to prevent pollution of the protected areas. The next idea was to knock the pollutant flow aside with another flow with flows of different speeds, one slowed down via diaphragms, another without slowing. This helped, but all the accessible area was soon swamped with pollutants.

Nevertheless, the successful flow shift was demonstrated using an optical channel with a beveled input. As a result, flow moves away from the optical components (Figure 4).

![Figure 4. Calculations for bevelled input (pollutant concentration distribution).](image)

Finally, the diagnostic channel of shape and size compatible with the respective space in the ITER DTS design was developed taking into account actual location of optical components and the laser beam paths (Figure 5).

![Figure 5. ITER diagnostic channel design.](image)

Performance of the proposed special box design was confirmed in 2D calculations. Then, the design was checked in comprehensive 3D calculations.
3. Results

Main results of the numerical simulation are presented in Figures 6-13. All distribution fields are shown at two time points of the pressure jump: over ~0.35 ms from the jump start and through the time equivalent to the jump duration (0.7 ms). 2D simulation results are presented for the box design providing thickness of deposited film $H = 0$ and compared with the 3D simulation results. It can be seen in Figure 13 that flows behavior provides that the protected surfaces stay clear not only during the pressure jump, but even after the pressure jump over. Interestingly, flow velocities near the protected surfaces are rather high (see Figure 8) but directed away from these surfaces (see Figures 10, 11). Thus, we can assume that the optical mirror launcher in ITER will be protected from the atomic Be contamination.

![Figure 6. Pressure field (Pa) for 2D and 3D in the symmetry plane at 0.35 ms.](image)

![Figure 7. Pressure field (Pa) for 2D and 3D in the symmetry plane at 0.7 ms.](image)

![Figure 8. Velocity magnitude field (m/s) for 2D and 3D in the symmetry plane at 0.35 ms.](image)

![Figure 9. Velocity magnitude field (m/s) for 2D and 3D in the symmetry plane at 0.7 ms.](image)
4. Summary

Effective protection of diagnostic components from pollution by Be sputtered from the ITER first wall should be intrinsic to the divertor diagnostic design for providing reliable information about divertor operation, including integrity of the divertor targets. The paper presents the special box designed for protection of the diagnostic laser optics from pollution by Be transferred with convection flows. The plasma sputtered Be can reach the divertor diagnostic optics during pressure jumps of 0.3 - 1 ms pulse duration, when plasma blobs with core plasma parameters drop on the divertor plates. The box operation based on the following phenomena: (1) deviation of the hydrodynamic flow away from the optical axis and (2) absorption/pumping provided by diffusion-related transfer of Be atoms to the box walls. The
design effectiveness of the proposed box, situated between ITER divertor plasma and the DTS diagnostic laser mirror launcher, was analyzed using ANSYS/FLUENT computational code via Volume-Of-Fluid (VOF) equations. The design was considered effective in case of no deposits on the protected surface. For the design selection, we started with preliminary 2D simulations. However, to take into account both friction and absorption of side walls of the gap between divertor cassettes, the box design was verified by 3D simulation. Comparison of the 2D and 3D simulations demonstrates significant friction effects on both the flow structure and parameters, i.e. 3D vs 2D "delay" gives more optimistic expectations concerning effectiveness of Be atoms absorption in stagnant flows. The suggested approach to protection against convective transport of plasma sputtered materials can be of use in other fusion machines and facilities with pulse plasma processing.

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