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Behaviour of plasma facing materials under VDE

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Abstract

Vertical Displacement Events represent one of the most damaging mechanisms for the plasma facing components. Energy deposition as high as 60 MJ/m^2 are deposited in less than 1 s. This phenomenon has been analysed numerically by means of the finite element technique. The results of the calculation have been compared with the experimental data obtained by simulation tests in the JUDITH electron beam facility.

1. Introduction

The Vertical Displacement Event (VDE) comprises an initial slow vertical drift phase of the plasma until it results in contact with the first wall, followed by the onset of a disruption and/or rapid loss of the remaining plasma thermal energy. The design goal is to minimise the number of VDEs to less than 10 during the Basic Performance Phase. This may be achieved by means of injections of impurity pellets to convert the VDE into a 'radial disruptions'. During the VDE a peak heat load on the first wall as high as 60 MJ/m^2 is foreseen on a time schedule of less than 1 s.

An experimental campaign was carried out in the JUDITH facility at Forschungszentrum Jülich aimed at investigating the behaviour of the plasma facing components during a VDE. A finite element analysis of the experiments was performed and this paper compares the numerical results with the experimental data.

2. Mock-up description

Both beryllium (Be) flat tile and carbon fibre reinforced carbon (CFC) monoblock were tested with different armour thicknesses.

As regards the Be-armoured components, two mock-ups manufactured by GEC are considered in this work (Fig. 1). The Be armour had thicknesses of 3 and 6 mm, respectively, and was joined to the CuCrZr copper alloy by induction brazing (CuMnSnCe braze at 720°C).

The CFC monoblocks were manufactured by means of Active Metal Casting (AMC®) by PLANSEE (Fig. 2). Two mock-ups are considered here: (1) SEP N31 CFC tile, 3 mm thick, DS-Cu tube, (2) Dunlop concept I CFC tile, 3 mm thick, CuCrZr tube.

3. Experimental conditions

A loading cycle of 1.5 s was applied on the armour of each component with a ramp-up, full power and ramp-down phase of 0.5 s each. The full power absorbed heat flux was 60 MW/m^2 and a total energy of 60 MJ/m^2 was deposited. The fraction of the incident flux actually absorbed by the armour material was determined by water calorimetry: absorption coefficients of 82% and 77% were found for the CFC and the Be, respectively. For the CFC monoblocks, the radiation cooling of the heated surface was balanced by a corresponding increase of the input power. As regards the Be components, a rapid increase of the evaporation cooling occurred during the test which can hardly be compensated by an increase of the input power. As a consequence the absorbed heat flux for the Be sample was somewhat lower. The mock-ups were actively cooled by water at 20°C, 3.5 MPa, 12 m/s. A twisted tape (twist ratio 2) was inserted into the cooling channels to prevent possible critical heat flux problems. A post-test analysis was carried out to check

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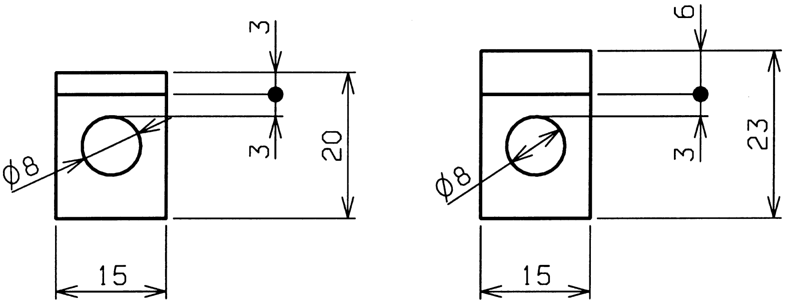

Fig. 1. Be mock-ups manufactured by GEC.

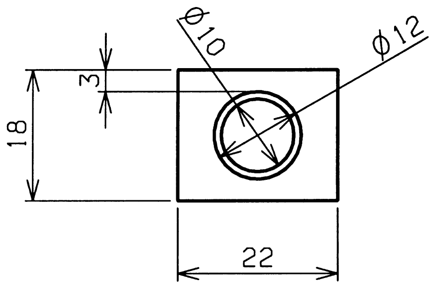

Fig. 2. CFC monoblocks manufactured by PLANSEE.

the integrity of the armour/heat sink joint and to evaluate the armour erosion/melting [1–3].

4. Numerical analysis

A 2D thermal analysis of the VDE tests was carried out by means of the ANSYS finite element code [4]. The heat transfer coefficient vs. wall temperature was computed by means of the EUPITER code [5] which implements the Sieder-Tate, the Bergles-Rohsenow and the Thom-CEA correlations in pure forced convection, at the onset of nucleate boiling and in the nucleate boiling regime, respectively. As regards the CFC thermal conductivity, mean values between N31 and Dunlop CFC were used in the calculation. As far as the thermal analysis of the Be mock-ups is concerned, the effect of the evaporation cooling was taken into account implementing a previously developed model in the ANSYS code [6]. In the case of the Be armour, the melting was also considered in the calculation.

5. Results

Fig. 3 shows a comparison between the numerical and experimental temperature of the heated surface of the CFC monoblock. The experimental data were measured by means of a pyrometer. The maximum values were 2926°C and 2614°C for the N31 and Dunlop CFC mock-ups, respectively. This difference can be easily explained by a higher thermal conductivity of the unirradiated Dunlop CFC with respect to the N31. The computed curve lies between the two experimental plots up to about 1.3 s. Since no radiation cooling was considered in the calculation, this fact confirms that the heat flux applied onto the mock-ups properly compensated the radiation losses. After 1.3 s the applied heat flux approaches the end of the ramp-down phase and no more compensates the radiation losses. As a consequence the computed surface temperature decreases with a lower rate than that experimentally measured.

Figs. 4 and 5 compare the computed and measured temperature of the heated surface of the Be mock-ups. The calculation assumes evaporation cooling during the VDE test, i.e. up to 1.5 s. During the ramp-up phase (from 0 to 0.5 s) a more rapid increase of the experimental surface temperature can be observed. This can be explained by the fact that the emissivity of Be depends strongly on the surface morphology and the BeO content. Furthermore it rapidly increases with temperature [7], and to try to overcome this problem, a two colour pyrometer, with a range of 1000–3500°C, was used additionally. It was calibrated in order to meet the reading of the one-colour pyrometer, with a range of 200–1100°C, in the overlapping region of sensitivity. However, the emissivity of the Be further increases above the melting point thus resulting in a higher measured temperature. During the full-power phase (0.5–1.0 s) the measured temperature seems to decrease. This phenomenon is not physically sound and can be explained by the formation of a vapour cloud over the melted Be surface. This cloud is practically transparent to the incident electron beam but not to the emitted infrared radiation. As a consequence the pyrometer sees a decreasing temperature. During the ramp-down phase (1.0–1.5 s) a good agreement between the numerical and experimental data can be observed. Probably the higher emissivity of the melted Be compensates the abovementioned absorption of the vapour cloud. After the ramp-down phase a more rapid decrease of the

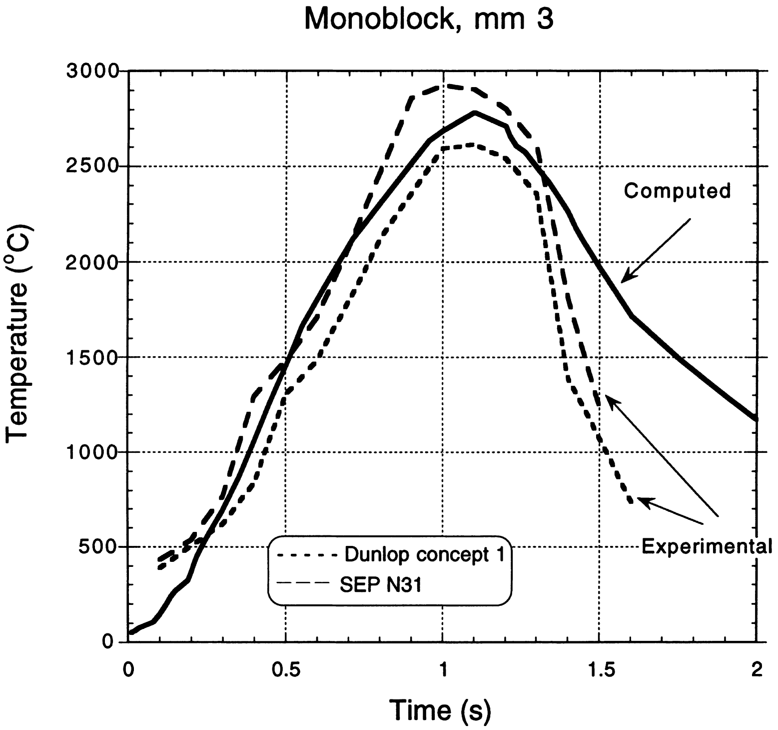

Fig. 3. Comparison between the computed and experimental surface temperature during the VDE test (CFC monoblock).

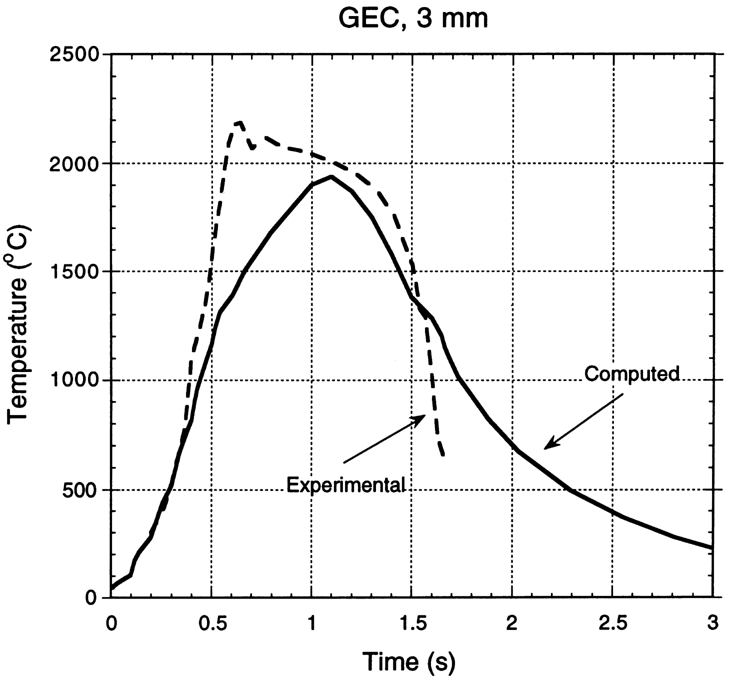

Fig. 4. Comparison between the computed and experimental surface temperature during the VDE test (3 mm thick Be armour).

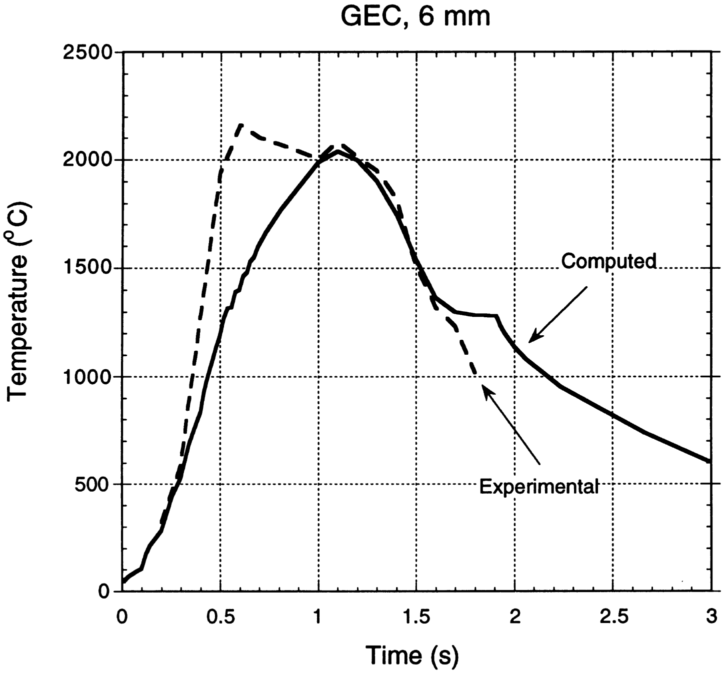

Fig. 5. Comparison between the computed and experimental surface temperature during the VDE test (6 mm thick Be armour).

experimentally measured surface temperature can be noted. This is because of the contribution of the evaporation cooling which could not have been taken into account in the calculation when no heat flux was applied. In the 6 mm thick mock-up a constant surface temperature was computed at the time 1.7–1.9 s because of the resolidification of the Be armour. This effect is less pronounced in the experimental curve. This can be explained mainly by the occurrence of convective motion in the melt layer which results in a more effective cooling [8]. Less important is the effect of the evaporation cooling in removing part of the latent heat of solidification (about 0.3 MW/m^2 [6]).

As far as the depth of the melt layer is concerned, a value of 1.02 and 1.25 mm was computed for the 3 and 6 mm thick Be armour, respectively. The corresponding experimental values are 0.9 and 1.5 mm, respectively [2].

6. Conclusions

To investigate the effects of the VDE heat loads on the armour materials, an experimental campaign was carried out in the JUDITH electron beam facility. A comparison between the experimental and the numerical results was performed. Good agreement was found for the measured and computed surface temperature as far as the CFC monoblock mock-ups are concerned. Scatter of the results are mainly due to the different thermal conductivity of the CFC grades.

More complex and, to some extent, uncertain is the interpretation of the results regarding the Be armoured mock-ups. In fact several phenomena occur during the surface melting, namely the rapid change of the emissivity, the formation of a vapour cloud over the heated surface which masks the emitted infrared radiation, the evaporation cooling. All these phenomena have an impact on the measured and real surface temperature. From a numerical stand point, one should consider that the thermal transient analysis has to simulate a rapid phenomenon like the VDE, to include the melting and resolidification of Be and to account for the radiation cooling. Considering all these difficulties and uncertainties, the agreement between the measured and computed temperatures can be considered satisfying. The scatter between the maximum measured and computed temperature during the transient is within a 10–15% range. A similar scatter range was observed while compared the computed and experimental melt layer depth.

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