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Numerical simulation of airflow characteristics during the loss of vacuum accident of CFETR

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ABSTRACT

During a loss of vacuum accident (LOVA) of China Fusion Engineering Test Reactor (CFETR), the high velocity airflow will result in the migration, re-suspension even explosion of the radioactive dust deposited in the vacuum vessel (VV) during plasma burning. In addition, large amounts of hydrogen may be produced from the exothermic reaction between tungsten and water/steam. In order to minimize the risk of explosion and the leakage of radioactivity, the airflow characteristics must be well studied at the first step. In this paper, a break due to a failed component is assumed to take place at the equatorial port. The numerical simulation has been performed by using ANSYS CFX code with a simplified VV model of CFETR. The airflow field during LOVA has been studied in detail under different initial pressure and first wall (FW) temperature. The results show that the FW temperature significantly affects the pressurization process. Besides, the friction velocity is also greatly affected by the FW temperature and initial pressure. From the 3D airflow distribution, the velocity near the lower part of torus can reach up to 87.4 m/s. This study provides indispensable basis for the research about dust resuspension, migration, dust/hydrogen explosion and the radiological safety of CFETR.

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Introduction

The China Fusion Engineering Test Reactor (CFETR), which aims to bridge the gaps between the International Thermonuclear Experimental Reactor (ITER) and the demonstration reactor (DEMO), is a tokamak-type machine and the next device in the roadmap for the realization of fusion energy in China. CFETR has a major radius of R = 6.6 m and a minor radius of a = 1.8 m in the 2016 version [1]. During the operation of CFETR, a large quantity of neutron activated [2] dust in micron size scales will be produced and deposited in the VV. The dust is formed by the interaction between plasma and the plasma facing components (PFCs). According to the conceptual design of Water Cooled Ceramic Breeder (WCCB) blanket [3] for CFETR, it employs the operation conditions of pressurized water reactor, namely 15.5 MPa pressure and inlet/outlet temperature of 285 °C/325 °C. The air ingress into VV will also be heated by the boundary. In case of in-vessel loss of coolant accident (LOCA), the high pressurized water converts into steam immediately due to the drastic changes of pressure [4]. The high temperature steam may react with the hot dust

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and PFCs material to produce a large amount of hydrogen through the chemical reaction [5]:

$$W + 3H_2O \rightarrow 3H_2 + WO_3 \quad (1)$$

Thus, a series of hazards potentially arise from air ingress into the VV due to a failure of the confinement vacuum boundary [5]. In case of LOVA, the air ingress into VV will mix with hydrogen and dust to form a combustible mixture. The high-speed airflow during LOVA may cause the migration and resuspension of dust. The abnormal presence of air with dust and hydrogen may cause a risk of explosion and lead to even more serious consequences [6–8]. The LOVA is the first stage of the accident sequences and the airflow characteristics are important to the safety of CFETR because it can induce hazards and risks as follows:

(1) Plasma disruption and shutdown of CFETR.
(2) Pressurization of VV and oxidation of in-vessel materials. According to the existing research [9–12], the mass flow rate of the airflow will affect the airflow characteristics and pressurization rate of the VV.
(3) Dust re-suspension and migration. According to the theory of Rock'n Roll (R'n R) model [13], the re-suspension of the particles is based on a competition between moments of airflow forces (lift and drag) and adhesive forces (van der Waals) on the particle [14]. However, the friction velocity of the airflow directly influences the airflow forces according to T. Gélain's work [14]. The friction velocity is given by:

$$u^* = \sqrt{\frac{\tau}{\rho}} \quad (2)$$

where ρ is the fluid density (kg m^{-3}) and τ is the shear stress at the wall (Pa).

Besides, the airflow field is crucial to the following migration and transport of the dust.

(4) Hydrogen and dust explosion. In the routine operation of CFETR, a larger quantity of hydrogen isotopes such as tritium exists in the VV. Meanwhile, the deposited dust would re-suspend under the forces of airflow. The mass flow rate of the air will influence the fraction of the hydrogen and dust which may bring a risk of explosion.
(5) Radioactive materials release. In the future fusion devices, Li-based materials are widely used as the tritium breeder by several blanket concepts [3,15–18]. A large amount of tritium will be produced in the blanket. The tritium and the dispersed dust are radioactive source terms which may potentially release to the environment with the airflow during LOVA.

Therefore, it is indispensable to study the airflow characteristics of the LOVA comprehensively to provide basis for further safety analysis for CFETR. Up to now, a series of researches on LOVA have been conducted by experiments and numerical simulations. M. Benedetti et al. [9] carried out a set of simulations to compare with experiments to study the airflow behaviors in STARDUST under different conditions. The results showed that the initial pressure inside the chamber did not influence the maximum velocity critically. C. Bellecci et al. [10–12] established a two-dimensional STARDUST model to validate the numerical method by comparing the simulation results with experimental data. The results showed good consistency. T. Gelain et al. [14] established a three-dimensional model for the VV of ITER to investigate the friction velocity field in the ITER tokamak during LOVA. Therefore, it is a feasible way by adopting Computational Fluid Dynamics (CFD) method for the research.

In this paper, characteristics of the airflow field in the VV, such as the velocity field, friction velocity, mass flow rate, air density and temperature distribution, have been studied in detail. CFD methodology has been applied to simulate the airflow characteristics by ANSYS-CFX [19]. Firstly, the description of LOVA cases is presented in section Description of LOVA cases. The theoretical equations, model parameters, boundary conditions and initial conditions for calculation based on the mesh independence analysis and turbulence model selection are shown in section Numerical model. In section Simulation Results, the simulation results of hypothetical break with different initial pressure and initial FW temperature are displayed. Then, a discussion is presented in section Discussion. Finally, conclusions are given in section Conclusions.

Description of LOVA cases

Two accident scenarios of LOVA, namely the LOVA with different FW temperature and the LOVA with different initial pressure, were selected to be analyzed in this article. The purpose is to evaluate the consequences and characteristics of air ingress into the VV during maintenance or some specific operational periods.

Base case

The hypothetical event is the rupture of the equatorial component of the VV boundary during maintenance. The accident will cause the air leak into the VV and consequently a rapid pressurization of the VV. In this base case, the initial temperature of in-vessel components is assumed to be 298 K during the process of LOVA while maintenance operation is performed.

FW temperature sensitivity study

Nevertheless, the LOVA may take place at any time of the operation period. The temperature of the components is obviously higher than ambient temperature when plasma is burning. Therefore, the effects of different FW temperature should be taken into account during the LOVA. Temperature at the FW is set to range from about 673 K (operating temperature) [20] to 298 K (ambient temperature). According to the conceptual design of WCCB [3,20,23], it is supposed to stay the same for more conservative because of the decay heat release during the LOVA.

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