CFD Analysis of Loss Of Vacuum Accident for Safety Application in Experimental Fusion Reactor Facility

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Abstract: The aim of this paper is to characterize the flow field inside an experimental fusion device during a Loss of Vacuum Accident (LOVA). In an experimental nuclear fusion facility dust is generated both during normal machine operations and by macroscopic erosion of the plasma facing materials due to intense thermal loads. This dust can be mobilized by air ingress in case of LOVA threaten safety of workers and public. A small facility, Small Tank for Aerosol Removal and Dust (STARDUST), was set up in order to perform experiments in which the dust mobilization can be studied in a volume with the initial conditions (pressure and walls' temperature) similar to those existing in fusion reactors. A COMSOL model which is capable of predicting the flow field during a LOVA in an experimental nuclear fusion facility is being developed at EURATOM-Quantum Electronics and Plasma Physics Research Group (University of Rome "Tor Vergata") in collaboration with ENEA Frascati laboratories. In this paper we will show experimental results, numerical results and the comparison between them.

Keywords: Loss of Vacuum Accident (LOVA); Fusion reactors;

1. Introduction

1.1 LOVA in ITER

The aim of fusion research is to develop a prototype fusion power plant that is safe and reliable, environmentally responsible and economically viable. ITER will be the world's largest experimental facility that aims to demonstrate the scientific and technical feasibility of fusion power. This facility is a long-pulse tokamak with elongated plasma and single null poloidal divertor. The nominal inductive operation produces a DT fusion power of 500MW for a burn length of 400 s, with the injection of 50MW of auxiliary power[0]. In a fusion experimental reactor the dust is generated during normal machine operations and by macroscopic erosion of the plasma facing materials due to intense thermal loads that occur during Edge Localized Modes (ELMs), plasma disruptions (PD) and Vertical Displacement Events (VDEs). This dust, mainly accumulated closeness the divertor zone, can be mobilized outside the Vacuum Vessel (VV) in case of LOVA threatening public safety because it may contain tritium, may be radioactive from activation products, and may be chemically reactive and/or toxic. A LOVA is a Design Basis Accident (DBA) event in fusion reactors [1]. Several studies on fundamental phenomena have been carried out in order to investigate the features of LOVA events both for the wet and dry case [2,3,4,5,6,7] and also reference events for ITER were postulated [8]. One of the main issue is to develop methods of computational analysis for the accident scenarios. An experimental facility, STARDUST, has been developed and utilized to validate new computational models capable of predicting the flow field for dust resuspension and transport in fusion reactor LOVA scenarios.

1.2 The STARDUST design

STARDUST is a stainless steel horizontal cylinder (internal volume 0.17 m3) closed by two lids [10] (Fig 1). STARDUST is equipped with an automatic data acquisition system that allows the control of internal pressure, wall temperature and air flow inlet in order to carry out the experiments at the desired initial conditions (see table 2). When the initial conditions are reached the control system opens the flow meter inlet valve and then the air flows inside the tank with a flow rate of 27 l/min in order to achieve a pressurization rate of 300 Pa/s typical in the ITER LOVA reference events (EX_A). In order to test the CFD model by analytical and experimental comparisons an experiment is being performed in which the ingress occurs by pressure difference between the atmospheric condition and the internal condition of the tank (EX_B) without an inlet flow rate imposed. Air inlet simulates the loss of vacuum event.

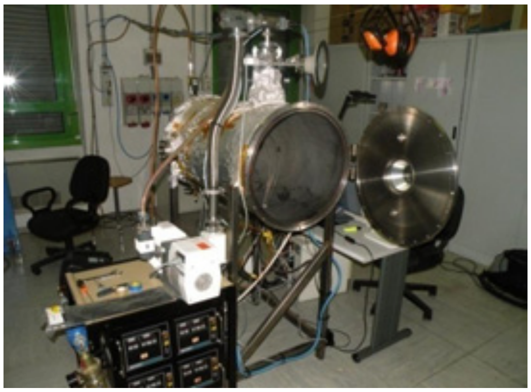

Figure 1: STARDUST facility

The air flow passes through two valves positioned in the back lid respectively at the middle of the tank, if an equatorial port failure occurs (A), and at the bottom of the tank (B), if a divertor port failure occurs [10,11,12,13,14]. The experiments have been carried out introducing a semi cylindrical obstacle made of stainless steel, which simulates the presence of structures, in particular the divertor, inside the ITER VV [13,14] . In order to take into account the influence of the space between limiter and divertor, as in the VV of ITER, a slit has been realized on the obstacle (Fig 2).

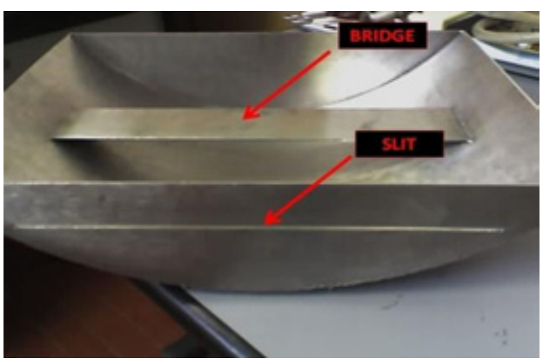

Figure 2: Obstacle

In the experimental campaign have been evaluated punctual flow velocity values, at 20cm from the inlet section, obtained in two different internal conditions:

- Experiments without obstacle (VA_WO for A inlet and VB_WO for B inlet valve);
- Experiments with obstacle, in order to understand better the influence of structures (like divertor) present inside STARDUST facility ((VA_O and VB_O);

The pressure transducer measures the difference of pressure (PΔ) between a pressure reference tube (static pressure Ps) and the pressure measured by the head of sensor (total pressure Pt). When the initial conditions inside the tank have been reached the controller allows the acquisition. For the calculation of velocity magnitude the equation

$$v = \sqrt{\frac{2\gamma R \bar{T}_{mean}}{M(\gamma - 1)}\left[\left(\frac{P_\Delta + P_s}{P_s}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \quad (1)$$

has been used where γ is the ratio of the specific heat of the fluid at constant pressure to the specific heat of the fluid at constant volume, R is the universal gas constant, T_{mean} is mean temperature measured by internal thermocouples and M is the air molecular mass. The pressurization rate is measured at the top of the chamber with a Pirani sensor.

Molar mass (Air)	M	28,966	kg/kmol
Inlet temperature	T0	294,15	K
Inlet pressure	p0	101325	Pa
Inlet density	ρ0	1,200	kg/m3
Inlet specific heat capacity at constant pressure (100-1000K)	Cp0	967,3	J/KgK
Inlet specific heat capacity at constant volume (100-1000K)	Cv0	680,3	J/KgK
Inlet Cp/Cv ratio	γ0	1,422	
Inlet dynamic viscosity (Sutherland)	η0	1,81E-05	Pa*s
Inlet kinematic viscosity	ν0	1,51E-05	m2/s
Inlet speed of sound	vs0	346,5	m/s
Inlet critical pressure	pc0	53157	Pa

Vessel air temperature	T1	294,15	K
Vessel air static pressure	p1	112,9226	Pa
Vessel air density	ρ1	0,001337	kg/m3
Inlet specific heat capacity at constant pressure (100-1000K)	Cp1	967,3	J/KgK
Inlet specific heat capacity at constant volume (100-1000K)	Cv1	680,3	J/KgK
Vessel air Cp/Cv ratio	γ1	1,422	
Vessel air dynamic viscosity (Sutherland)	η1	1,81E-05	Pa*s
Vessel kinematic viscosity	ν1	1,35E-02	m2/s
Vessel air speed of sound	vs1	346,5	m/s
Vessel air critical pressure	pc1	59,2	Pa
Vessel wall temperature		294,15	K

Table 1: STARDUST inlet and internal conditions

2. Vessel Filling Analysis

A closed form solution for pressure vs. time (tr) can be obtained under the following simplifying assumptions:

- Ideal gas with constant specific heat
- Zero velocity and spatially uniform properties in the vessel
- Isentropic flow through the constant area inlet
- Adiabatic or isothermal behavior depending on the length of transient

Flow is initially choked since the pressure is below the critical value. The time to reach the critical pressure and the pressurization rate for choked and unchoked solution for the isothermal (I) and adiabatic (A) case are ($P_{r,i}$ is the initial pressure)[2]:

$$t^{I}_{r,C} = \left(\frac{2}{\gamma+1}\right)^{1/2} - P_{r,i}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (2)$$

$$t^{A}_{r,C} = \frac{1}{\gamma}\left(\frac{2}{\gamma+1}\right)^{1/2} - \frac{P_{r,i}}{\gamma}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (3)$$

$$P^{I}_{r}(t_r) = P_{r,i} + \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} t_r \text{ (choked) } (4)$$

$$P^{A}_{r}(t_r) = P_{r,i} + \gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} t_r \text{ (choked) } (5)$$

$$P^{I}_{r}(t_r) = \left[1 - \left[\sqrt{1 - P_{r,C}^{\frac{\gamma-1}{\gamma}}} - \sqrt{\frac{\gamma-1}{2\gamma^2}}\ t_r - t^{I}_{r,C}\right]^2\right]^{\frac{\gamma}{\gamma-1}} \quad (6)$$

$$P^{A}_{r}(t_r) = \left[1 - \left[\sqrt{1 - P_{r,C}^{\frac{\gamma-1}{\gamma}}} - \sqrt{\frac{\gamma-1}{2}}\ t_r - t^{A}_{r,C}\right]^2\right]^{\frac{\gamma}{\gamma-1}} \quad (7)$$

Initial (i) and final (f) pressure (p) and temperature (T), characteristic time (Tchar which is given in terms of the vessel volume V, inlet cross sectional area A, and sound speed based on the temperature of the surroundings c, tchar=V/Ac), time (Tc) to reach critical pressure and the filling time for the STARDUST facility are shown in Table 2.

	Isothermal	Adiabatic
Pi(Pa)	112,9226	112,9226
Pf(Pa)	101325	101325
Ti(K)	294,15	294,15
Tf(K)	294,15	418,254
tchar(s)	8,0650	8,0650
tc(s)	7,3133	5,1433
tf(s)	17,7344	13,0084

Table 2: STARDUST conditions and vessel fill times

3. Model Description

Simulation of the thermal and flow fields into STARDUST has been carried on, with COMSOL Multiphysics® (CM). The implemented model is based on the fully compressible formulation of the continuity equation and momentum equations

$$\frac{\partial p}{\partial t} + \nabla\ \rho u\ = 0$$

$$\rho\frac{\partial u}{\partial t} + \rho u\cdot\nabla u = -\nabla p + \nabla\cdot\left[\eta\ \nabla u + \nabla u^{\ T} - \left(\frac{2}{3}\eta - \kappa_{dv}\right)\nabla\cdot u\ I\right] + F \quad (8)$$

and (9)

- ρ : density (kg/m3)
- u : velocity vector (m/s)
- p : pressure (Pa)
- η : dynamic viscosity (Pa·s)
- F : body force vector (N/m3)

The stress tensor used describes a Newtonian fluid, with an added term Kdv. This term expresses the deviation from Stokes' assumption, which states that the fluid particles are in thermodynamic equilibrium with their neighbors. For the resolution of the system of equations mentioned before we have used the technique Galerkin Least-Squares (GLS) in such way to be gotten a stable discretization of the elements.

The equations that govern the conduction in the solid domain and the conduction/convention in fluid domain are the following:

$$\rho C_p\left[\frac{\partial T}{\partial t}+u\cdot\nabla T\right]=-\nabla\cdot q+\tau:S-\frac{T}{\rho}\frac{\partial \rho}{\partial T}\bigg|_p\left(\frac{\partial p}{\partial t}+u\cdot\nabla p\right)+Q$$

$$-n\cdot(-k\nabla T)=h(T_{inf}-T) \quad (10)$$

- **ρ** : density (kg/m^3)
- **C_p** : is the specific heat capacity at constant pressure (J/(kg·K))
- **T** : absolute temperature (K)
- **u** : velocity vector (m/s)
- **q** : heat flux by conduction (W/m^2)
- **p** : pressure (Pa)
- **τ**: viscous stress tensor (Pa)
- **S** : strain rate tensor (1/s):
- **Q** : contains heat sources other than viscous heating (W/m^3)
- h: heat transfer coefficient (W/(m^2·K)).

Developed analyses have been conducted in transitory regime with an ideal fluid assumption.

Name	Expression	Unit
rho_tank	p*MM/(R0*T_tank)	kg/m^3
eta_tank	0.0000178*(T_tank/288.15)^1.5*(288.15+110)/(T_tank+110)	Pa*s

Table 3 : Thermo-physic properties

We designed model geometry of the STARDUST facility:

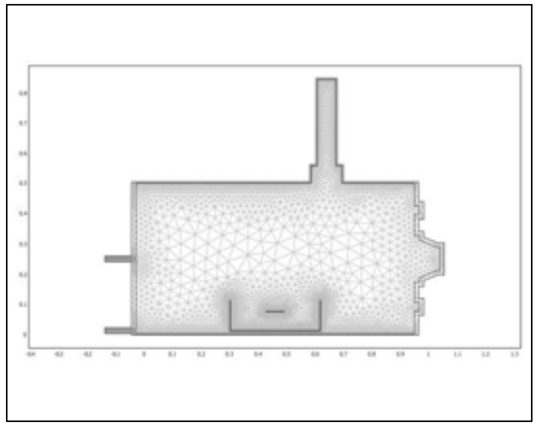

Figure 2: Flow field VA_WO

Number of degrees of freedom	42053
Number of mesh points	5446
Number of elements (Triangular)	10388
Number of boundary elements	1412
Number of vertex elements	90
Minimum element quality	0.591
Element area ratio	0.001

Table 4: Mesh parameter

The boundary conditions reply the operational conditions of the facility (see Appendix1):

Boundary	3-4, 6, 11, 13, 20-33, 36-37, 40-46, 49-50, 53-62, 73-78, 85-86, 89-91	10
Type	Wall	Inlet
name	Internal	Inlet
intype	Velocity	Pressure, no viscous stress
walltype	No slip	Slip
x-velocity (u0)[m/s]	0	0
Pressure (p0)[Pa]	0	(t<=topen)*(p_inlet *(-6*(t/topen)^7+7*(t/topen)^6+(t>topen)*(p_inlet_max)

Table 5: Boundary conditions

where topen is the aperture time of the inlet valve (2ms).

4. Results

A section of the tank for the all experimental configurations characterizing the flow field is shown in following figures:

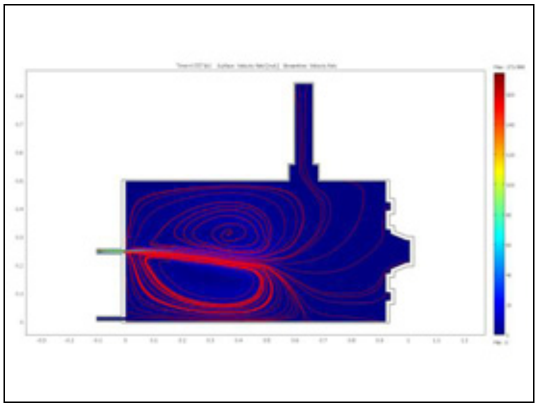

Figure 4: Flow field VA_WO

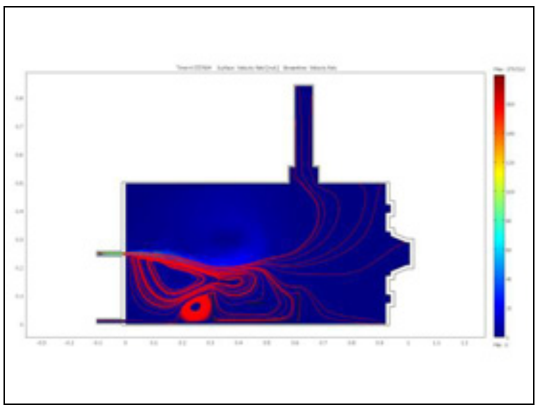

Figure 5: Flow field VA_O

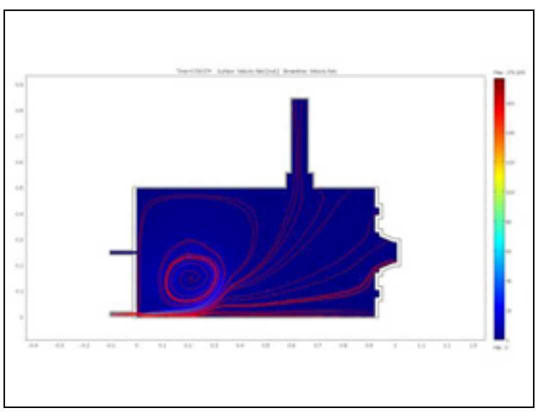

Figure 6: Flow field VB_WO

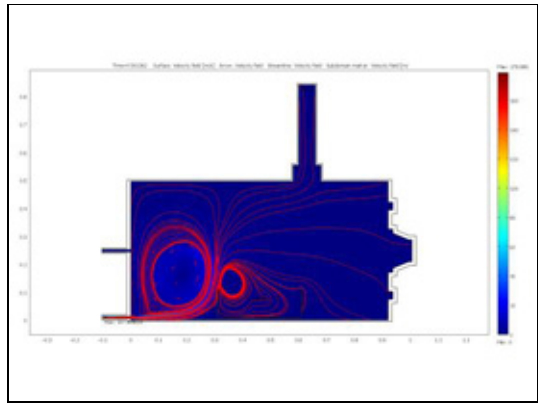

Figure 7: Flow field VB_O

Experimental and model results are compared in the following figure:

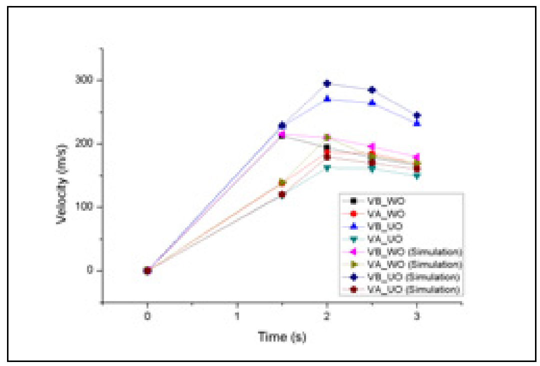

Figure 8: Velocity@20cm from inlet

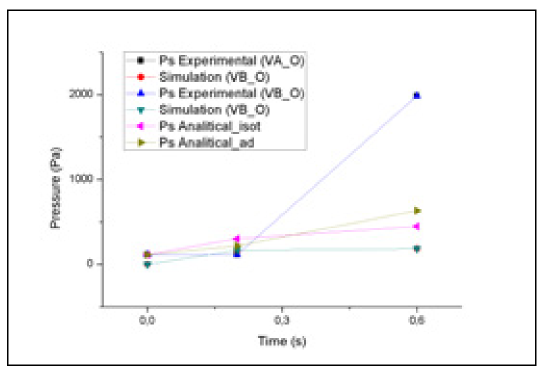

Figure 9: Pressure vs. Time

The model matches closely the experimental data with a slightly faster fill time. Simulations and experiments showed that the presence of an obstacle in STARDUST influences the dust's mobilization solely in case of leakage at divertor ports level (valve B). This result matches with experiments done in 2007 experimental campaign [13,14] in which we have measured the quantity of dust resuspended in case of LOVA. The percentage of dust resuspended, that simulates a LOVA at divertor level is lower in case of obstacle inside the chamber [13,14]. These results match with experimental and numerical results obtained in the current work. In fact the velocity values measured without obstacle (VB_WO) are higher than velocity values measured with obstacle (VB_O).

7. Conclusions and future works

Comsol models for short transients (~ 1,5 s) have given reasonable results. Future work will focus on obtaining accurate results for longer transients, resolving flow features such as shocks and boundary layers, implementing of dust resuspension models, improving mesh and geometry impact on cpu time, including turbulence model behavior. The dust resuspension models include most of the transport phenomena relevant for ITER. The 3D numerical code describing the dust mobilization in STARDUST facility will be improved by means of COMSOL software and comparison will be made with experimental data acquired during 2007, in order to validate the model. Then the same model will be adapted to a toroidal shape and an optical diagnostic for measurement of dust mobilization evolution will be chosen and studied. The results will be useful for the design of optical ports in a new experimental facility with a geometrical shape similar to ITER foreseen to be realized.

8. References

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8. Appendix 1