IMPLEMENTATION AND ASSESSMENT OF THE DELAYED EQUILIBRIUM MODEL FOR COMPUTING FLASHING CHOKED FLOWS IN A MULTI-FIELD CFD CODE

Matthieu Duponcheel, Jean-Marie Seynhaeve and Yann Bartosiewicz
Institute of Mechanics, Materials and Civil Engineering
Université catholique de Louvain,
Place du Levant, 2, 1348 Louvain-la-Neuve, Belgium
matthieu.duponcheel@uclouvain.be, jm.seynhaeve@uclouvain.be,
yann.bartosiewicz@uclouvain.be,

ABSTRACT

In the context of a Loss of Coolant Accident (LOCA), it is important to be able to accurately predict the water/vapor flow rate through a breach in the primary circuit. This paper deals with the CFD-implementation of the Delayed Equilibrium Model (DEM), which physically tackles thermodynamic non-equilibrium conditions prevailing in the flashing flow process near the breach section. This approach is originally a 1D three-phase model for choked or critical flow rate in steady state or quasi-steady state conditions. The DEM has been recently assessed against six different sets of experimental data. The chosen CFD platform, NEPTUNE_CFD developed by EDF-CEA with the support of AREVA-NP and IRSN (France), solves conservation equations for an n-field problem. The proposed implementation is based on the balance equations written for three fields: the saturated vapor phase, the saturated liquid phase and the metastable liquid phase. The vaporization index correlation is properly used to implement the interfacial mass and heat transfer between the three fields. The NEPTUNE_CFD code is then used to simulate the Super-Mobydick experiments performed at CEA. The results are compared with the original DEM developed in-house.

KEYWORDS
Flashing Choked Flow, LOCA, NEPTUNE_CFD, DEM

1. INTRODUCTION

In the context of nuclear reactor safety, a pipe breach in the primary circuit is the initiator of a Loss of Coolant Accident (LOCA). The calculation of leak rates involving the discharge of water and steam mixtures plays an important role in the modeling of LOCA's for both GEN II and GEN III PWR and BWR reactors, and also for the Supercritical Water Reactor of GEN IV. Indeed, the flow through the breach determines the depressurisation rate of the system and the time to core uncover, which in turn are of major concern for when and how different mitigation auxiliary systems will be initiated and be efficient (SBLOCA, [1]). The pipe involved could be a main coolant pipe leading to a large break LOCA (LBLOCA), or a pipe connected to the main coolant loop (e.g. an ECC line, defect at a pressurizer valve) leading to an intermediate or small break.

The flow through a breach in the primary loop will initially be choked or critical, i.e. the mass flow rate is independent of the downstream flow conditions [15]. Indeed, for a certain value of the pressure difference, the flow in a pipe connecting two vessels at different pressures becomes choked and any further decrease of the pressure in the downstream vessel does not result in a change of the mass flow

rate. This limit, which corresponds to the maximum mass flow rate between both vessels, exists because the acoustic signal related to the pressure decrease can no longer propagate upstream of the critical section. This condition occurs when the fluid velocity reaches the propagation velocity or the speed of sound and it is strongly influenced by the flashing of the pressurized liquid. Therefore, an accurate prediction of the critical mass flow rate requires the proper modeling of the flashing phenomenon.

The modelling of critical flows in several of the thermal-hydraulics codes is based on semi-empirical models which, in general, require user defined adjustment factors to obtain a satisfactory agreement with data in individual situations. In this regard, more universal models are required. The Delayed Equilibrium Model (DEM) [3-12] was validated and assessed using the same set of calibrated coefficients against a wide range of operating conditions and geometry and is thus more universal. This model considers a metastable liquid phase in addition to the saturated liquid and vapour phases.

The DEM model was originally developed in a one-dimensional framework. This paper investigates the possibility to adapt this proven model to a more general three-dimensional framework in a multi-field Computational Fluid Dynamics (CFD) solver. The chosen CFD platform was NEPTUNE_CFD developed by EDF-CEA with the support of AREVA-NP and IRSN (France), which has already been used to simulate critical flows using a two-phase model [13]. The implementation of the DEM in NEPTUNE_CFD was naturally performed using three fields corresponding to the three phases of the model.

This paper is organized as follows: first, the original DEM model for 1-D equations is presented, then its adaptation to the framework of 3-D multi-field CFD is detailed. Eventually, validation results on the Super Moby Dick experiment are presented.

2. DELAYED EQUILIBRIUM MODEL (DEM) FOR CHOKED FLASHING FLOWS

In the section, the Delayed Equilibrium Model (DEM) [3-12] and the related hypotheses are presented. This model was developed for one-dimensional steady flows as an improvement over the Homogeneous Equilibrium Model (HEM).

Before presenting the equations of the model, let us first describe the flashing phenomenon which can occur in a pipe. At the inlet, the fluid enters the pipe in a subcooled state (T_{in}, p_{in}) which is such that $p_{in} > p_{sat}(T_{in})$. The pressure decreases due to the friction, and reaches saturation at a section "s". Between section "s" and the onset of flashing, the liquid is metastable. The onset of flashing occurs at section "o", where the pressure p_o has been deduced experimentally and is typically [14]:

$$p_o = 0.975 p_{sat}(T_{in}). \tag{1}$$

The location of point "o" depends on the inlet subcooling and on the pressure loss, and thus on the mass flow. Here we will assume that the inlet subcooling and the mass velocity are such that the onset of flashing is located inside the pipe. Between point "o" and the pipe outlet, a two-phase bubbly flow develops rapidly, and the pressure gradient increases as the flow accelerates. If the pressure at the outlet is low enough, the flow is choked, and the outlet pressure is the critical pressure p_c. One can expect that the over-heating (or metastability) of the liquid phase does not vanish instantaneously at point "o", but persists within the two-phase part of the flow, depending, on the one hand, on the intensity of the heat transfer from the bulk of liquid to the interface and, on the other hand, on the pressure decrease rate.

In order to model the persistence of the metastability beyond the onset of flashing, the DEM considers the existence of three "phases" which coexist: the metastable fluid (subscript "l,M"), the saturated liquid

("l,sat") and its saturated vapor ("v,sat"). At a certain position *z* along the pipe, only a mass fraction *y* of the fluid is in its saturated state while the remaining *(1-y)* fraction is still in a metastable state. The mass fraction of saturated vapor in the mixture is denoted *x*. Therefore, the thermodynamic properties (enthalpy and specific volume) of the 3-phase mixture (denoted by the subscript "m") are obtained as

$$h_m \triangleq (1-y)h_{l,M} + xh_{v,sat} + (y-x)h_{l,sat} \tag{2}$$

$$v_m \triangleq (1-y)v_{l,M} + xv_{v,sat} + (y-x)v_{l,sat}\,. \tag{3}$$

A mechanical equilibrium is assumed between the 3 phases, i.e.

$$w_m = w_{l,M} = w_{l,sat} = w_{v,sat} \tag{4}$$

where, *w* is the axial velocity. The governing equations of this steady 1-D flow are

$$\begin{aligned} \frac{d}{dz}\left(\frac{w_m A}{v_m}\right) &= 0 \\ v_m\frac{dp}{dz} + w_m\frac{dw_m}{dz} &= -v_m\frac{P_w}{A}\tau_w - g\cos\theta \\ \frac{dh_m}{dz} + w_m\frac{dw_m}{dz} &= \frac{v_m}{w_m}\frac{P_w}{A}q_w - g\cos\theta \end{aligned} \tag{5}$$

where A is the cross section of the pipe, P_w is its perimeter, τ_w is the wall shear stress, g is the gravity acceleration, θ is the angle between the pipe axis and the vertical and q_w is the wall heat flux. The thermodynamic properties of the saturated phases only depend on the pressure. Some hypotheses are required to characterize the evolution of the metastable phase. In the DEM, it is assumed that this phase is "frozen" [7-9] and that its evolution is isentropic, so that its properties only depend on the pressure. Therefore,

$$dh_{l,M} - v_{l,M}dp = TdS = 0 \tag{6}$$

and thus

$$\left(\frac{\partial h_{l,M}}{\partial p}\right)_S = v_{l,M}. \tag{7}$$

Furthermore, the variations of its specific volume are neglected. With these hypotheses, the unknown quantities in the equation system (5) are the pressure p, the velocity w_m, the quality x and the mass fraction y. An additional closure relation is thus required to solve this system:

$$\frac{dy}{dz} = f(p, y, T_{l,M})\,. \tag{8}$$

Féburie et al. [15] have proposed a correlation for flows through steam generator tube cracks and for subcooled inlet conditions:

$$f(p, y, T_{l,M}) = 0.02\frac{P_w}{A}(1-y)\left[\frac{p_{sat}(T_{l,M}) - p}{p_{crit} - p_{sat}(T_{l,M})}\right]^{0.25} \tag{9}$$

where p_{crit} is the pressure of the critical point of the fluid. This relaxation law expresses that the decrease of the mass fraction of superheated liquid *d(1-y)* over an element of length *dz* is proportional to the remaining quantity of superheated liquid, and to the metastability ratio to the power 0.25. This relaxation law has been generalized and recently improved to take into account not only the nucleation at the wall (constant C_1) but also in the bulk of the flow (constant C_2) These constants have been determined from an extensive number of experiments in small as well as in very large nozzles ([3,15-19]). This improved relaxation law can be written as:

$$f(p, y, T_{l,M}) = \left(C_1 \frac{P_w}{A} + C_2 \right) (1 - y) \left[\frac{p_{sat}(T_{l,M}) - p}{p_{crit} - p_{sat}(T_{l,M})} \right]^{C_3} \tag{10}$$

using the calibrated coefficients [20] :

$$\begin{aligned} C_1 &= 8.39 \times 10^{-3} \quad [\text{-}] \\ C_2 &= 6.34 \times 10^{-1} \quad [\text{m}^{-1}] \\ C_3 &= 2.28 \times 10^{-1} \quad [\text{-}] \end{aligned} \tag{11}$$

The system of equations (5), supplemented by the closure law (8), can be written in a matrix form

$$\begin{bmatrix} v_{v,sat} - v_{l,sat} & v_{l,sat} - v_{l,M} & \begin{matrix} x v'_{v,sat} \\ +(y-x) v'_{l,sat} \\ +(1-y) v'_{l,M} \end{matrix} & -\frac{v_m}{w_m} \\ 0 & 0 & 1 & \frac{w_m}{v_m} \\ h_{v,sat} - h_{l,sat} & h_{l,sat} - h_{l,M} & \begin{matrix} x h'_{v,sat} \\ +(y-x) h'_{l,sat} \\ +(1-y) h'_{l,M} \end{matrix} & w_m \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \frac{dx}{dz} \\ \frac{dy}{dz} \\ \frac{dp}{dz} \\ \frac{dw_m}{dz} \end{bmatrix} = \begin{bmatrix} \frac{v_m}{A} \frac{dA}{dz} \\ -\frac{P_w}{A} \tau_w - \frac{1}{v_m} g \cos\theta \\ -g \cos\theta + \frac{v_m}{w_m} \frac{P_w}{A} q_w \\ f(p, y, T_{l,M}) \end{bmatrix} \tag{12}$$

where the *(.)'* operator denotes the derivative with respect to the pressure. This system can be solved from the inlet, with imposed pressure and velocity, up to the critical section using a space-marching algorithm. The critical condition of the model is a vanishing determinant of the system. After some manipulations, it appears to correspond to the classical definition of the speed of sound

$$w_c = \sqrt{\left(\frac{\partial p}{\partial \rho_m} \right)_{S_m, y}}. \tag{13}$$

A shooting method is required to determine the critical mass flow such that the critical section is located at the pipe exit.

3. IMPLEMENTATION OF THE DEM IN THE NEPTUNE_CFD SOLVER

NEPTUNE_CFD [21] is a 3-D finite volume solver for the multi-field Navier-Stokes equations which solves the mass, momentum and energy equations for each field. This multi-field formalism differs significantly from the one used in the DEM where the number of independent variables is much smaller.

Furthermore, the DEM model was developed for 1-D flows using quantities averaged over a cross-section whereas NEPTUNE_CFD uses cell-averaged quantities for 3-D flows. The equations solved by NEPTUNE_CFD will be briefly presented and, then, the implementation of the DEM in that framework will be explained.

3.1. The NEPTUNE_CFD solver

NEPTUNE_CFD, developed jointly by EDF R&D and CEA, solves the multi-field Navier-Stokes equations for an arbitrary number of fields. One particular case is two-phase flows which are solved using two fields. For the field *k*, NEPTUNE_CFD solves

- the mass balance equation

$$\frac{\partial}{\partial t}\left(\alpha_k \rho_k\right) + \frac{\partial}{\partial x_i}\left(\alpha_k \rho_k u_{k,i}\right) = \sum_{p \neq k} \Gamma_{(p \to k)} \tag{14}$$

  with α_k the volume fraction, ρ_k the density, $u_{k,i}$ the velocity and $\Gamma_{(p\to k)}$ the interfacial mass transfer rate from field *p* to field *k*,

- the momentum equations

$$\begin{aligned}\frac{\partial}{\partial t}\left(\alpha_k \rho_k u_{k,i}\right) + \frac{\partial}{\partial x_j}\left(\alpha_k \rho_k u_{k,i} u_{k,j}\right) \\ = \frac{\partial}{\partial x_j}\left(\alpha_k \tau_{k,ij}\right) - \alpha_k \frac{\partial p}{\partial x_i} + \alpha_k \rho_k g_i + \sum_{p \neq k} I_{i,(p \to k)}\end{aligned} \tag{15}$$

  with $\tau_{k,ij}$ the stress tensor, g_i the gravity acceleration, p the pressure and $I_{i,(p\to k)}$ the interfacial momentum transfer rate from field *p* to field *k,*

- the energy equation for the total enthalpy H_k

$$\begin{aligned}\frac{\partial}{\partial t}\left(\alpha_k \rho_k H_k\right) + \frac{\partial}{\partial x_j}\left(\alpha_k \rho_k H_k u_{k,j}\right) \\ = -\frac{\partial}{\partial x_j}\left(\alpha_k q_{k,j}\right) + \alpha_k \frac{\partial p}{\partial t} + \alpha_k \rho_k u_{k,i} g_i + \sum_{p \neq k}\left(\Gamma_{(p \to k)} H_k + \Pi_{(p \to k)}\right)\end{aligned} \tag{16}$$

  with $q_{k,j}$ the heat flux density and $\Pi_{(p\to k)}$ the interfacial heat transfer from field *p* to field *k*. This equation neglects the viscous dissipation and the energy transfer related to the interfacial momentum transfer.

The density $\rho_k = \rho_k(p, h_k)$ can be computed using several thermodynamic tables available in NEPTUNE_CFD. Many physical models for the interfacial transfer terms and for turbulent fluxes are available to compute bubbly/boiling flows, free surface flows and droplet-laden flows [22].

The equations (14)-(16) are solved using a compressible pressure-based algorithm which is first order accurate in time. This algorithm is a fractional time-step method using an “alpha-pressure-energy cycle” that ensures conservation of mass and energy and allows strong interface coupling source terms [23].

3.2. Implementation of the DEM using interfacial transfer terms

The implementation of the DEM in NEPTUNE_CFD is performed using the multi-field capability of the solver and considering each phase of the DEM model as a field in NEPTUNE_CFD, thus leading to a 3-field model. The thermodynamic properties of each field are obtained from the CATHARE thermodynamic tables for water (either liquid or vapor) available in NEPTUNE_CFD.

The two fields corresponding to the saturated liquid and vapor must be constrained to remain saturated. This is enforced by adding strong interfacial heat transfer terms tending to return each phase to the saturation temperature:

$$\begin{aligned}\Pi_{(v,sat\to l,sat)} &= \alpha_{l,sat}\rho_{l,sat}C_{p,l,sat}\frac{T_{sat}(p)-T_{l,sat}}{\tau}\\ \Pi_{(l,sat\to v,sat)} &= \alpha_{v,sat}\rho_{v,sat}C_{p,v,sat}\frac{T_{sat}(p)-T_{v,sat}}{\tau}\end{aligned} \tag{17}$$

where τ is the "return to saturation" time-scale which was here set to a very small value $\tau = 10^{-5}$ s. In order to guarantee a zero net interfacial energy transfer, the mass transfer between the saturated phases is directly related to the heat transfer by

$$\Gamma_{(v,sat\to l,sat)} = -\Gamma_{(l,sat\to v,sat)} = \frac{\Pi_{(l,sat\to v,sat)}+\Pi_{(v,sat\to l,sat)}}{H_{v,sat}-H_{l,sat}}. \tag{18}$$

The mechanical equilibrium, i.e. identical velocities for all the phases, is obtained by adding very large symmetrical drag forces between all the fields:

$$I_{i,(p\to k)} = \alpha_p\alpha_k F_D(u_{p,i}-u_{k,i}) \tag{19}$$

where the constant F_D was set to a very large value $F_D = 10^9$ [kg/m^3/s] so that $u_{p,i} = u_{k,i}$.

In the DEM, the mass conservation of the metastable phase reads

$$\frac{\partial}{\partial z}\left(\rho_m(1-y)w_m A\right) = \Gamma_{(l,M\to l,sat)}A \tag{20}$$

where ρ_m is the mean density computed as

$$\rho_m = \alpha_{l,M}\rho_{l,M} + \alpha_{l,sat}\rho_{l,sat} + \alpha_{v,sat}\rho_{v,sat}. \tag{21}$$

Taking the global mass conservation Eq. (5) into account, Eq. (20) becomes

$$\rho_m w_m \frac{\partial}{\partial z}(1-y) = \Gamma_{(l,M\to l,sat)}, \tag{22}$$

so that, the interfacial mass transfer rate is

$$\Gamma_{(l,M\to l,sat)} = -\rho_m w_m f(p,y,T_{sat}) = -\frac{\alpha_{l,M}\rho_{l,M}}{\Theta_{DEM}} \tag{23}$$

where the DEM time-scale Θ_{DEM} is defined as

$$\frac{1}{\Theta_{DEM}} = w_m \frac{f(p, y, T_{sat})}{(1-y)}. \tag{24}$$

This mass transfer rate is an average over a cross section of the pipe and takes into account both the nucleation at the wall, with the $C_1 P_w/A$ term, and the bulk nucleation, with the C_2 term. In the objective to develop a local version of the DEM, those two effects should be separated to obtain a variation of the mass transfer rate across the section. As the definition of the source term is intrinsically local, one can imagine to modify the DEM length scale A/P_w to take into account the distance to the wall. However, here as a first step, the length scale was kept constant in a cross-section in order to demonstrate the ability of NEPTUNE_CFD to solve this 3-field model and to assess its accuracy.

In order to satisfy the constrain that the net interfacial energy transfer is zero, the mass transfer from the metastable liquid to the saturated liquid must be related to some heat transfer between the two fields. In agreement with the hypothesis of a frozen metastable phase, it is assumed that there is no interfacial heat transfer to the metastable phase

$$\Pi_{(l,sat \rightarrow l,M)} = 0. \tag{25}$$

Consequently, the interfacial heat transfer to the saturated liquid must be

$$\Pi_{(l,M \rightarrow l,sat)} = \Gamma_{(l,M \rightarrow l,sat)} \left(H_{l,M} - H_{l,sat}\right) \tag{26}$$

to satisfy the energy balance.

The implementation in NEPTUNE_CFD was performed by adding a third field to the "bubbly flow" case setup. This allows to use the already implemented source terms between the two saturated phases. The source terms related to the metastable phase were implemented in user-defined functions. This implementation is thus 3-D ready, even thought the DEM length-scale is a function of the axial direction only.

4. SIMULATION OF THE SUPER MOBY DICK EXPERIMENTS

The implementation of the DEM in NEPTUNE_CFD was validated and assessed against the Super Moby Dick experiments, performed by CEA-Grenoble during the eighties [16]. Steady state two-phase critical flow conditions were measured in a long and in a short nozzle. The long nozzle has an elliptic convergent section at the entrance, followed by a straight pipe of about 0.380 m long and of 20 mm inner diameter, and ended by a 7° divergent section. The short nozzle has almost the same geometry without the divergent section. The measurements are reported for several inlet pressures and temperatures.

In this study, only the long nozzle was simulated and its geometry is shown in Fig. 1. The total simulated length is 0.921 [m] with the inlet located at $z = 0$ [m] and the beginning of the divergent at $z = 0.5$ [m]. Since the nozzle is axisymmetric, only a 1° sector was computed. As the DEM model in NEPTUNE_CFD is still uniform in a cross-section, a 1-D mesh, also shown in Fig. 1, was used to simulate the Super Moby Dick experiment. The mesh is uniform in the axial direction and two resolutions were used: 200 and 800 cells. Two inlet conditions were simulated: $T_{in} = 240.5$ [°C] and 249.4 [°C], both with a 40 bar inlet pressure. These cases correspond to the SMD 5b and 6b experiments, respectively. In the 6b case, the inlet state is vey close to saturation since the saturation temperature at 40 bar is $T_{sat}(40\ bar) = 250.35$ [°C]. The entering subcooled water is represented by the metastable phase in the DEM. Yet, for the model

to converge, the inlet volume fractions of the saturated phases were both set to 10^{-3}. The sensitivity to those inlet values should be investigated.

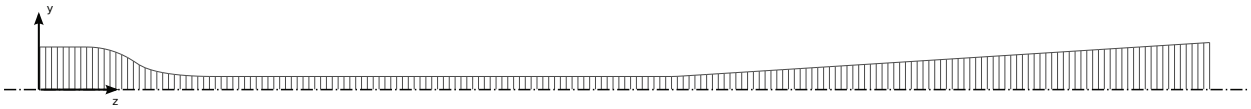

Figure 1. Geometry and 200-cell mesh of the Super Moby Dick experiment

The DEM implemented in NEPTUNE_CFD was compared to the experimental data as well as to the original implementation of the DEM using an iterative space-marching algorithm. It was also compared to a 2-phase model for flashing flows available in NEPTUNE_CFD. In this 2-phase model, the flashing is controlled using the interfacial enthalpy transfer terms for which the CATHARE1D-like flashing model 24] is used. This model was only computed using the finer mesh.

The results for the SMD 6b case, the closest to saturation, are shown in Fig. 2. Because of the space-marching algorithm, the results of original DEM are only available up to the critical section, i.e. for $z < 0.5$ [m]. In NEPTUNE_CFD, the whole nozzle is computed, including the divergent. However, the DEM was not designed to reproduce the physics of possible recondensation in this part, therefore, the emphasis is placed on the region upstream of the critical section which determines the critical mass flow. For the SMD 6b case, the original DEM is the closest to the experimental results. When implemented in NEPTUNE_CFD, the DEM tends to slightly underpredict the void fraction whereas the pressure decreases too quickly in the straight pipe after the contraction. Using the fine mesh improves the pressure profile, so that only the fine mesh will be used for the other case. The 2-phase model in NEPTUNE_CFD strongly overpredicts the flashing rate and thus the void fraction. The pressure drop in the convergent is not well predicted and, in the straight pipe, the pressure gradient is also too large and almost equal to that obtained using the DEM in NEPTUNE_CFD. The increased pressure loss in NEPTUNE_CFD may be due to the treatment of the wall shear stress in this 1-D configuration and should be further investigated. Even though this not the focus of the present investigation, it can be observed that, in NEPTUNE_CFD, the DEM model predicts a strong recondensation shock whereas the CATHARE1D-like 2-phase model doesn't. The mass flow rate the various models are compared in Table. 1. The DEM results are relatively close the experimental flow rate while the 2-phase model significantly underestimates the mass flow. This explains why the pressure drop in the convergent is too small when using the latter model.

For the SMD 5b case, as depicted in Fig. 3, the CATHARE1D-like 2-phase model of NEPTUNE_CFD very accurately reproduces the experimental results, both for the pressure and the void fraction. The mass flow (see Table 1) is also accurately predicted. The original DEM is even more accurate regarding the pressure and the void fraction profiles. However, the DEM in NEPTUNE_CFD predicts a mass flow significantly lower than the experimental one. Consequently, the pressure drop in the convergent is too small. The void fraction is relatively close to the experimental one but slightly larger. Similarly to the 6b case, the pressure loss in the straight part of the nozzle is too large. In this case, however, the slopes of the pressure profile for the two models in NEPTUNE_CFD are quite different.

Table I. Critical mass flow density

Mass flow density [kg/s/m2]	SMD	DEM	DEM NEPTUNE_CFD (200 cells)	DEM NEPTUNE_CFD (800 cells)	2-phase NEPTUNE_CFD
SMD 5b	32800	33267	-	28349	33253
SMD 6b	25200	25877	25060	24455	22421

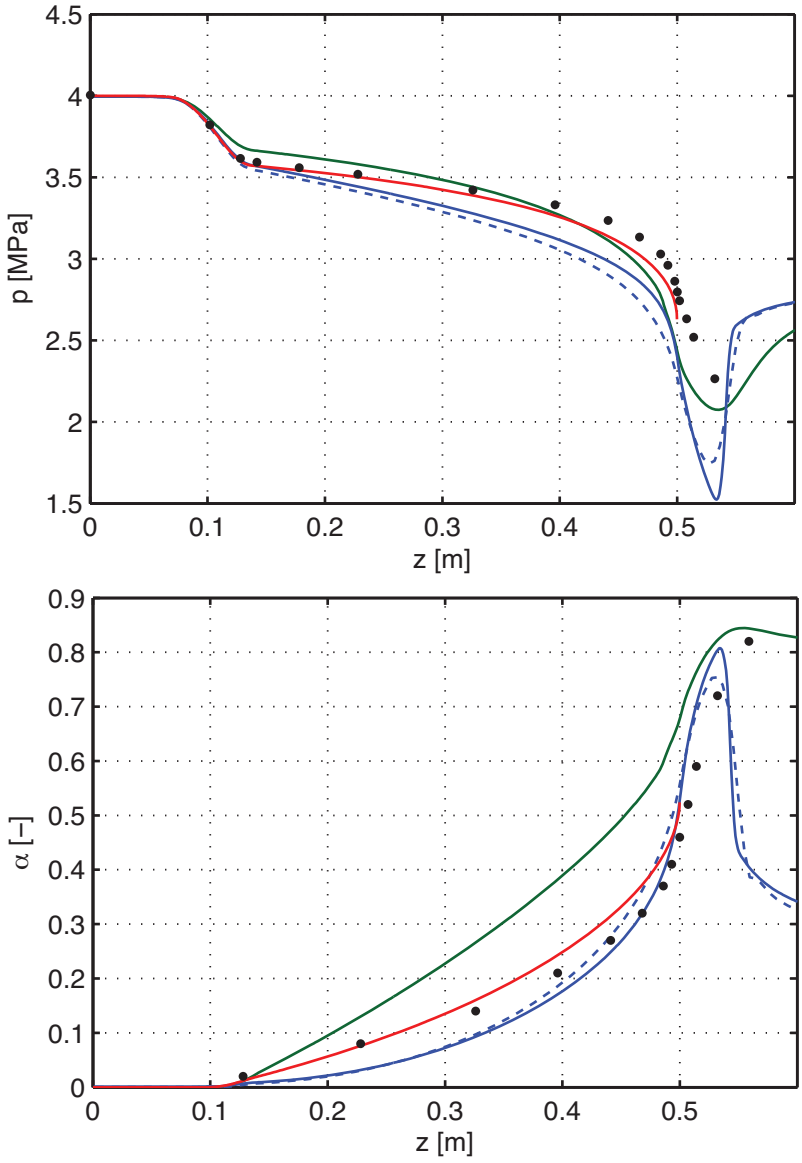

Figure 2. SMD 6b case : evolution of the pressure (top) and void fraction (bottom) along the nozzle : SMD experiment (black dots), DEM (red), DEM in NEPTUNE_CFD (blue) using a 200-cell mesh (dash) or a 800-cell mesh (solid) and a 2-phase model of NEPTUNE_CFD (green).

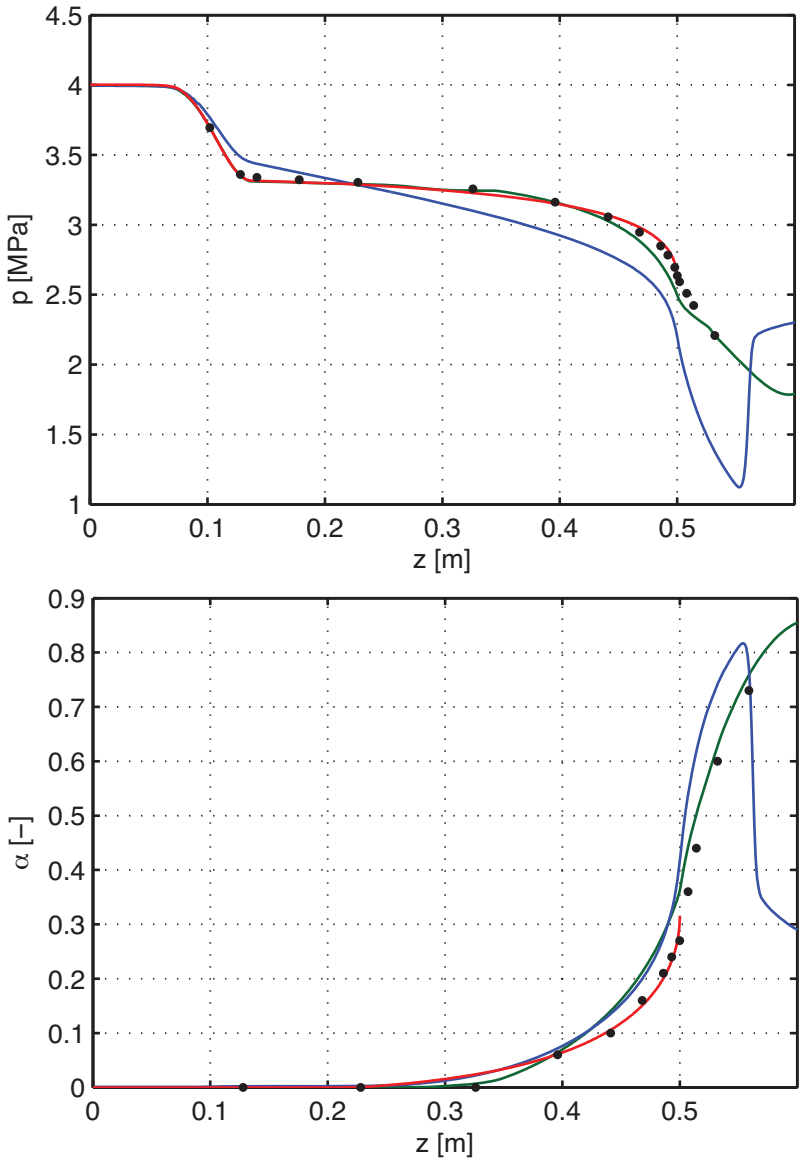

Figure 3. SMD 5b case : evolution of the pressure (top) and void fraction (bottom) along the nozzle : SMD experiment (black dots), DEM (red), DEM in NEPTUNE_CFD (blue) and a 2-phase model of NEPTUNE_CFD (green).

5. CONCLUSIONS

This study dealt with the numerical simulation of flashing chocked flows using the Delayed Equilibrium Model (DEM), originally developed as a 1-D model of this kind of flows. The objective of this work was to implement this model into a more general 3-D multi-field CFD solver. The DEM was implemented in the NEPTUNE_CFD solver, developed jointly by EDF R&D and CEA, using three fields and by modifying the interfacial transfer terms. The current implementation is not fully local since the DEM length scale is still considered uniform in a cross-section and it does not take into account that the flashing occurs mainly at the wall. The development of a truly local DEM model to perform 2-D or 3-D simulations would be a natural continuation of the present work.

The implementation of the DEM in NEPTUNE_CFD was validated and assessed against two cases of the Super Moby Dick experiments. The results are in good agreement with the experiment for the case closer to saturation where the error on the critical mass flow is about 3%. However, the mass flow is under predicted by 13.5% in the case of the larger subcooling. Yet, in both cases, the results are not as accurate as those obtained using the original DEM and its iterative space-marching algorithm. A possible explanation of the difference between the two implementations of the DEM is the treatment of the wall shear-stress and the induced pressure drop. The investigation of this issue is ongoing.

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