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Abstract

This work takes place in steam generators flow studies and we consider here steady state three dimensional two-phase (liquid and gas) flows. The main goal is to improve the modeling of kinetic imbalance between the phases. We present a method that solves the mixture (liquid-gas) mass and enthalpy equations, and two momentum equations: one for the mixture and one for the gas. This choice is equivalent of solving the gas and the liquid momentum equations, but it is better suited to the Chorin projection method used for the pressure calculation. Solving two momentum equations instead of solving only the one for the mixture introduces the use of correlations for the gas-liquid friction but avoids the use of a correlation for the drift velocity and opens the way to a finer analysis of the relative dynamic behavior of each phase.

Key words: Steam Generator, Two-phase Flow, Finite element

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1 Introduction

The steam generators are the large heat exchangers located between the nuclear core and the turbines in pressurized water reactors. The primary fbw is a loop that links the core and the steam generator. It goes through the exchanger inside a U-shaped tube bundle. The secondary fbw is another loop that links the steam generator and the turbines. Inside the exchanger this secondary loop fbws around the tubes and several supporting structures. The figure B.1 shows a scheme of this kind of steam generator. Under normal operating conditions the primary fbw is in liquid phase at the pressure 15 MPa, whereas the secondary fbw, being at the pressure 7 MPa, enters the exchange area in liquid phase but starts to boil and leaves this area in a two-phase situation with a void fraction around 0.8.

These physical and geometrical conditions present two main features : the secondary fbw is actually three dimensional around complicated structures and presents the thermodynamic behavior of phase change. It is important to have a good detailed simulation of this fbw in order to prevent damage on the solid structures due to the vibrations induced by the fbw and due to the sludge deposit.

Several industries in electric power or nuclear reactor manufacturing have developped numerical simulation tools to this purpose (Inch and Shill (1980), Singhal et al. (1983), Aubry et al. (1989)).

We have also developped our own tool based on a finite element method and presented in detail in Grandotto and Obry (1996).

In all these works an homogenization of the tube bundle has been used and the two-phase fbw has been modeled by a three equations system : the three conservation equations (mass, momentum and energy) relative to the liquid-gas mixture. This model is presented in section 2 and our method to solve this model is recalled in section 3.

The kinematic and thermodynamic disequilibrium are taken in account by specific correlations. This is convenient when these non-equilibriums are not too strong. This is generally the case in the steam generators for the thermodynamic behavior, but not always for the kinematic one, in particular in the areas where the flow is strongly three dimensional such as the U-bend zone.

To improve the prediction of the flow we have developped an extended model to overcome the limitation of the drift-flux model (computation of the difference between the gas and the liquid velocities). In this extension, the momentum equations of the gas and of the liquid are used. This is presented in section 4 and its numerical solution is given in section 5. Finally applications and results are presented in section 6.

2 Three equations two-phase flow model

After averaging the mass, momentum and energy equations for each phase (see Hughes and Chen (1977)), we sum them to get a mixture description of the two-phase flow. Provided that the following assumptions hold,

- surface tension, viscous and turbulent dissipation are neglected and pressure terms are neglected in enthalpy balance equation,
- same pressure for steam and liquid,
- eddy viscosity model,
- time independant porosity (fixed homogenized solids),

we get :

(1) mass balance

$$\beta\partial_t\rho + \overrightarrow{\nabla}.(\beta\rho\overrightarrow{V}) = 0 \tag{1}$$

(2) momentum balance

$$\begin{aligned}&\beta\rho\partial_t\overrightarrow{V} + \beta\rho(\overrightarrow{V}.\overrightarrow{\nabla})\overrightarrow{V} + div(\beta x(1-x)\rho\overrightarrow{V_R}\otimes\overrightarrow{V_R})\\ &= \beta\rho\overrightarrow{g} - \beta\overline{\Lambda}\rho\overrightarrow{V} - \beta\overrightarrow{\nabla}P + div(\beta\mu_T(\overrightarrow{\nabla}\overrightarrow{V} + \overrightarrow{\nabla}^T\overrightarrow{V}))\end{aligned} \tag{2}$$

(3) enthalpy balance

$$\begin{aligned}&\beta\rho\partial_t h + \beta\rho(\overrightarrow{V}.\overrightarrow{\nabla})h + div(\beta x(1-x)\rho h_{fg}\overrightarrow{V_R})\\ &= \beta Q + div(\beta\chi_T\overrightarrow{\nabla}h)\end{aligned} \tag{3}$$

We solve in h, P and $\overrightarrow{V}$ variables. In order to compute ρ, x and h_{fg} as a function of h and P, we need thermodynamic tables : $\rho, x = f(P,h)$, $h_{fg} = f(P)$.

The μ_T, χ_T, $\overline{\Lambda}$, $\overrightarrow{V_R}$ terms are obtained by the use of a large set of semi-empirical closure relations (see Obry et al. (1990)). We use the Schlichting model for μ_T (Schlichting (1968)) and the drift-flux Lellouche-Zolotar model for $\overrightarrow{V_R}$ (Lellouche and Zolotar (1982)). This kinematic disequilibrium modeling is built as follow (Zuber and Findlay (1965)) :

$$\overrightarrow{V_R} = \overrightarrow{V_G} - \overrightarrow{V_L} \tag{4}$$

$$\overrightarrow{V} = x\overrightarrow{V_G} + (1-x)\overrightarrow{V_L} \tag{5}$$

$$\overrightarrow{j} = \alpha\overrightarrow{V_G} + (1-\alpha)\overrightarrow{V_L} \tag{6}$$

$$\overrightarrow{V_G} = \overline{\overline{C_0}}\,\overrightarrow{j} + \overrightarrow{V_{Gj}} \tag{7}$$

$\overline{\overline{C_0}}$, the distribution tensor, and $\overrightarrow{V_{Gj}}$, the limit gas velocity, are defined by the following relations :

$$\overline{\overline{C_0}}\langle\widetilde{\alpha}\rangle\langle\widetilde{\overrightarrow{j}}\rangle = \langle\widetilde{\alpha}\,\widetilde{\overrightarrow{j}}\rangle \; ; \; \overrightarrow{V_{Gj}} = \frac{\langle\widetilde{\alpha}\widetilde{\overrightarrow{V_{Gj}}}\rangle}{\langle\widetilde{\alpha}\rangle} \tag{8}$$

where $\tilde{.}$ means local in space and time value and $\langle.\rangle$ means average value over the control volume.

The following three dimensional extension has been used :

$$\overline{\overline{C_0}} = \begin{bmatrix} C_{0T} & 0 & 0 \\ 0 & C_{0T} & 0 \\ 0 & 0 & C_{0w} \end{bmatrix} \tag{9}$$

The heat source Q in the enthalpy equation is linked to the resolution of an energy balance equation for the primary flow. To evaluate this term, we include other correlations about the heat exchange coefficient and the wall temperature.

3 Numerical method

We are looking for a stationary solution as a limit of the time dependent equations. But as we can neglect wave effects we eliminate the time term in Equation (1).

The numerical scheme is based on an unstructured finite element method with trilinear hexahedral elements and a Crank-Nicholson time scheme. The h and $\overrightarrow{V}$ variables are approximated at the nodes and the P variable is approximated by a constant value in each finite element. Other details of the finite element setup can be found in (Grandotto and Obry (1996))

The diffusion terms are implicit like the friction one (momentum). Generally, the advection and drift terms are explicit. At each time step ($\equiv$ outer iteration to solve non linear coupled equations), we first solve the primary fluid energy equation (fully implicit FEM) to get the enthalpy source term Q. Thus, we resolve the enthalpy equation and then the coupled mass-momentum system by the Chorin-Gresho method, see Gresho and Chan (1990). We use a conjugated gradient method (CGM) preconditioned by the diagonal ($\equiv$ inner iterations).

The algorithm is :

Step 1 : set the thermodydamic state, compute the closure terms and solve the primary energy equation to compute the primary temperature,

$$\left\{ \begin{array}{c} \rho^n, x^n = f(P^n, h^n) \ , \ h_{fg}^n = f(P^n) \\ \Lambda^n, \mu_T^n, \chi_T^n, V_R^n = f(P^n, h^n, V^n) \\ T_P^{n+1} \ = \ \text{primary enthalpy equation solution} \\ S^n = f(P^n, h^n, V^n, T_P^{n+1}) \end{array} \right\} \tag{10}$$

Step 2 : solve the secondary energy equation to compute the secondary enthalpy,

$$\frac{1}{\Delta t}\left[M(\rho^n) + D(\chi_T^n)\right] h^{n+1} = \frac{1}{\Delta t}\left[M(\rho^n) - N(\rho^n V^n)\right] h^n + S^n - D_F^n + BC \tag{11}$$

Step 3 : solve the secondary momentum equation to compute the intermediate velocity (V^*),

$$\frac{1}{\Delta t}\left[M(\rho^n)+D(\mu_T^n)+F(\Lambda^n\rho^n)\right]V^* = \frac{1}{\Delta t}\left[M(\rho^n)-N(\rho^n V^n)\right]V^n+\rho^n g$$
$$+BP^n - D_F^n + BC \qquad (12)$$

Step 4 : apply the projection procedure to update the velocity and to compute the pressure,

$$\left\{\begin{array}{c} \left[B^T M^{-1} B\right]\lambda = B^T \rho^n V^* \\ \rho^n V^{n+1} = \rho^n V^* - M^{-1} B\lambda \\ P^{n+1} = P^n + \frac{2\lambda}{\Delta t} \end{array}\right\} \qquad (13)$$

Where M is the mass matrix, D is the diffusion matrix, N is the convective matrix, B is the gradient/divergence matrix, D_F is the drift-flux term and BC is the boundary conditions term. V^* is an intermediate velocity, λ is a pressure corrector and Δt is a time step.

4 Four equation two-phase flow model

In order to overcome some limitations of the drift-flux model, mainly when there are strong two or three dimensional effects we have developed a two-phase flow model with two momentum equations, one for each phase :

$$\beta\alpha_k\rho_k\partial_t\overrightarrow{V_k}+\beta\alpha_k\rho_k(\overrightarrow{V_k}.\overrightarrow{\nabla})\overrightarrow{V_k} = \beta\alpha_k\rho_k\overrightarrow{g}-\beta\alpha_k\overrightarrow{\nabla}P-\beta\overline{\Lambda}_k\overrightarrow{V_k}$$
$$-\beta\overline{\Lambda}_{Ik}\overrightarrow{V_k}+\beta\overline{\Lambda}_{Ik'}\overrightarrow{V_{k'}}-a_k(\overrightarrow{V_k}-\overrightarrow{V_{k'}})+div(\beta\alpha_k\mu_{Tk}(\overrightarrow{\nabla}\overrightarrow{V_k}+\overrightarrow{\nabla}^T\overrightarrow{V_k})) \qquad (14)$$

where $k = G\ or\ L$ and $k' = L\ or\ G$

It has been assumed that the two phases have the same pressure.

The relations (4) and (5) show that there are only two independant velocities in the set $[\overrightarrow{V};\overrightarrow{V_R};\overrightarrow{V_L};\overrightarrow{V_G}]$. So, solving any couple of these ones is mathematically equivalent. Nevertheless, if it is possible to build an equation for $\overrightarrow{V_R}$, it is a quite complicated one and solving it is not easy. On the other hand, following several tests we have done, solving in $\overrightarrow{V_L}$ and $\overrightarrow{V_G}$ is not compatible with the Chorin-Gresho projection. The reason is that there is only one pressure in the system which is best fitted to correct only the mixture velocity $\overrightarrow{V}$. These considerations led us to keep the solving of the mixture momentum equation (2) and to add the resolution of one phasic momentum equation. We have choosen the gas momentum equation because the dynamic of this phase is more sensitive than the liquid one (at least in our applications).

The closure of the equation 14 needs interfacial momentum transfer laws. We use the same as the ones developed in the code CATHARE (Bestion (1990).

5 Extended numerical scheme

We keep the algorithm used for the three equation model and add the solving of the gas velocity :

$$\left\{\begin{array}{c} given\ V_{ri}\ and\ V_i \\ \\ Compute\ V_{i+1}\ (mixture\ momentum\ equation) \\ \\ V^0_{Gi+1} = V_{i+1} + (1 - x_i)V_{ri} \\ \\ Compute\ V_{Gi+1}\ (gas\ momentum\ equation) \\ \\ V_{ri+1} = (V_{Gi+1} - V_{i+1})/(1 - x_i) \end{array}\right\} \tag{15}$$

Solving the gas momentum equation is very similar to solving the mixture momentum equation and we can re-use the same methods (solver).

We have to cope with the areas where the flow is liquid (the bottom part of a steam generator for instance). We apply a filter based on the value of the void fraction to not solve the gas momentum equation on the points located inside these areas.

We need a initial value for the relative velocity $\overrightarrow{V_R}$. For this we start the algorithm with only the three equation model and after a few iterations (typically 10) we turn to the full model using the value of $\overrightarrow{V_R}$ given by the drift-flux modeling.

Our tests have shown that we have to use a mimimum value of the void fraction to start solving the gas momentum equation and we found that 10^{-3} was a good choice.

Finally we need a gas velocity boundary value at the boilling front. This is similar to find the value of the gas velocity when the gas appears. We use the same correlation that gives the limit gas velocity in the drift-flux modeling.

6 Applications and results

We have compared the results obtained with the four equations model on two test cases for which we had results with the three equations model (Grandotto and Obry (1996)).

6.1 One dimensional test case

This test case is a one dimensional reduction of the steam generator mock-up Clotaire (Campan and Bouchter (1988)). It is equivalent to a vertical tube having a horizontal section area of 0.16 m^2 and that is 7 m in height. This tube contains a tube bundle with a porosity equal to 0.66 and nine support plates. The heat source is 1.4 W/m^3, the inlet enthalpy is 1.19 10^5 J/kg, the inlet mass flow rate is 108 kg/s and the outlet pressure is 0.88 MPa. The figure B.2 gives the vertical evolution of the gas velocity. One can see the effect on the gas velocity of the strong variation of the pressure due to the support plate, details that can not be obtained with the three equation model. Nevertheless the two models give the same global evolution.

6.2 Two dimensional test case

We consider here the flow inside the experiment Frida from Electricité de France (Pierotti and Bussy (1987)) devoted to the study of the bottom part of the steam generators. The flow goes through a square pitch tube bundle, the tubes are electrically heated and the power is 3 MW/m^3. The geometry is shown on the figure B.3. The fluid is Freon R114. The boundary conditions are the following :

- at the inlet the mass flow rate is 10 kg/s and the enthalpy is 79,100 J/kg corresponding to a thermodynamic quality of -0.034.

- at the outlet the pressure is fixed at the value 0.386 MPa.

The figures B.4, B.5 and B.6 give the comparison of the results obtained with the three and the four equations models for the gas velocity and the void fraction at three different horizontal levels. These results are similar and the differences between the models is less than the precision of the measurements. We recall that the results of the three equations model were in agreement with the experimental values (see Grandotto and Obry (1996)).

7 Conclusion

We have presented in this paper a four equation two-phase flow model for the simulation of the flow inside the steam generators. The results obtained with this model have been compared to those given by the three mixture equation model. This model is then ready to be applied to new simulations of the Clotaire mock-up when new three dimensional measurements in the U-bend area of the tube bundle will be avalaible.

Acknowledgements

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A Nomenclature

- $\overrightarrow{\nabla}\overrightarrow{V} = \frac{\partial V_a}{\partial x_b}$

- $\overrightarrow{\nabla}^T \overrightarrow{V} = \frac{\partial V_b}{\partial x_a}$
- a_k : momentum transfer due to mass transfer coefficient
- $\overline{\overline{C_0}}$: distribution tensor
- $\overrightarrow{G}$: mixture mass flux (= ρ $\overrightarrow{v}$)
- $\overrightarrow{g}$: gravity (m s^{-2})
- h : mixture specific enthalpy (J kg^{-1})
- h_{ls} : saturated liquid specific enthalpy (J kg^{-1})
- $\overrightarrow{j}$: superficial velocity (m s^{-1})
- h_{fg} : latent heat (J kg^{-1})
- P : pressure (Pa)
- Q : heat source (W m^{-3})
- t : time (s)
- T_P : primary temperature (K)
- $\overrightarrow{V}$: mixture velocity (m s^{-1})
- $\overrightarrow{V_G}$: gas velocity (m s^{-1})
- $\overrightarrow{V_{Gj}}$: limit gas velocity (m s^{-1})
- $\overrightarrow{V_L}$: liquid velocity (m s^{-1})
- $\overrightarrow{V_R}$: relative velocity ($\overrightarrow{V_G} - \overrightarrow{V_L}$, m s^{-1})
- x : static quality ($\equiv \frac{h-h_{ls}}{h_{fg}}$)
- α : void fraction
- $\alpha_G = \alpha$
- $\alpha_L = 1 - \alpha$
- β : porosity
- χ_T : turbulent diffusion coefficient for the mixture energy equation (kg m^{-1} s^{-1})
- μ_T : two-phase turbulent dynamic viscosity (kg m^{-1} s^{-1})
- μ_{Tk} : turbulent dynamic viscosity of the phase k (kg m^{-1} s^{-1})

- ρ : mixture density (kg m^{-3})
- ρ_k : density of the phase k (kg m^{-3})
- $\overline{\Lambda}$: two-phase friction tensor (s^{-1})
- $\overline{\Lambda}_k$: parietal friction tensor of the phase k (kg m^{-3} s^{-1})
- $\overline{\Lambda}_{Ik}$: interfacial friction tensor of the phase k (kg m^{-3} s^{-1})

B Figures

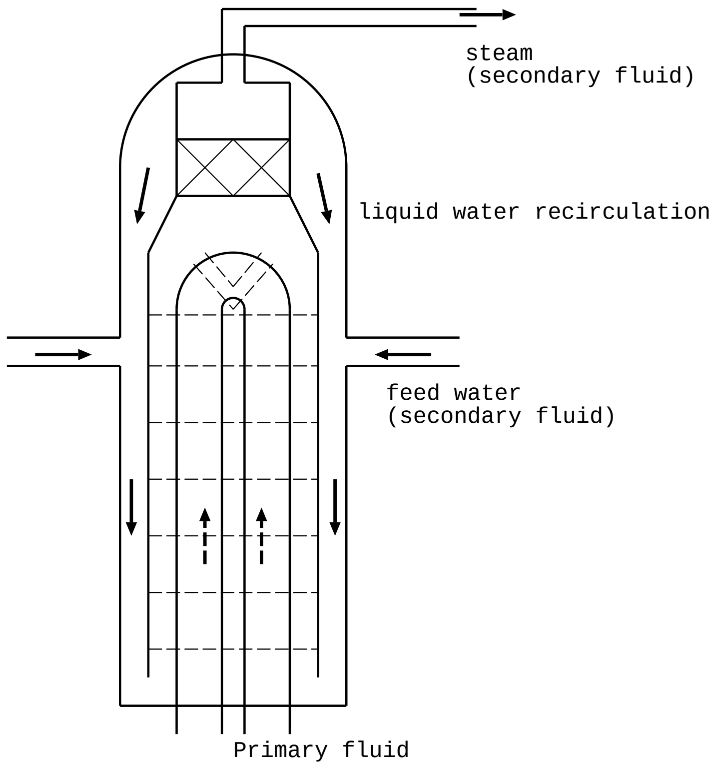

Fig. B.1. French nuclear steam generator (scheme)

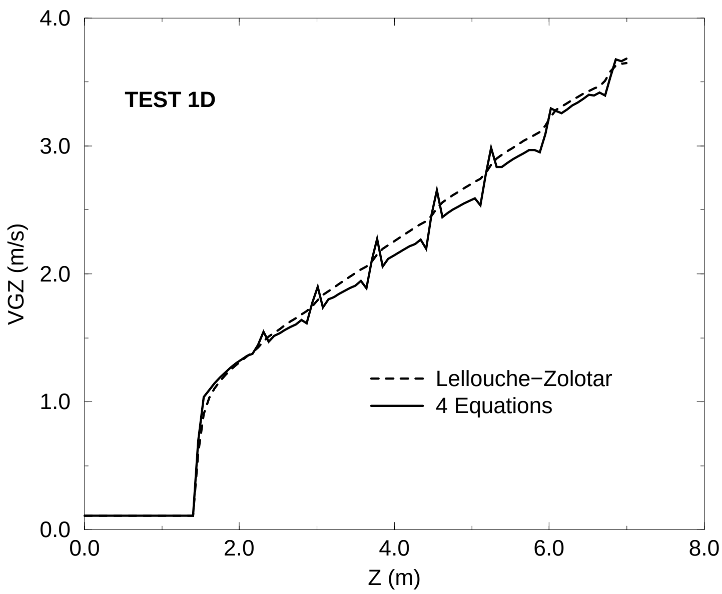

Fig. B.2. One dimensional gas velocity results

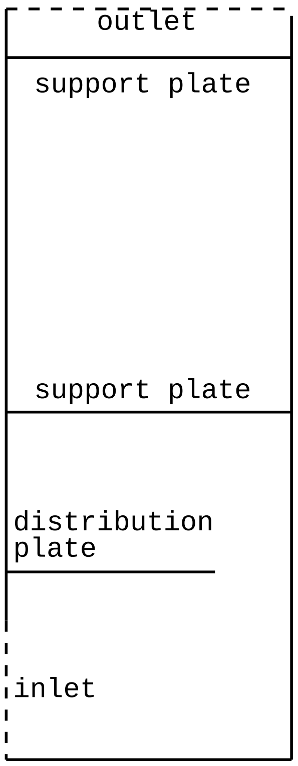

Fig. B.3. Two dimensional steam generator test

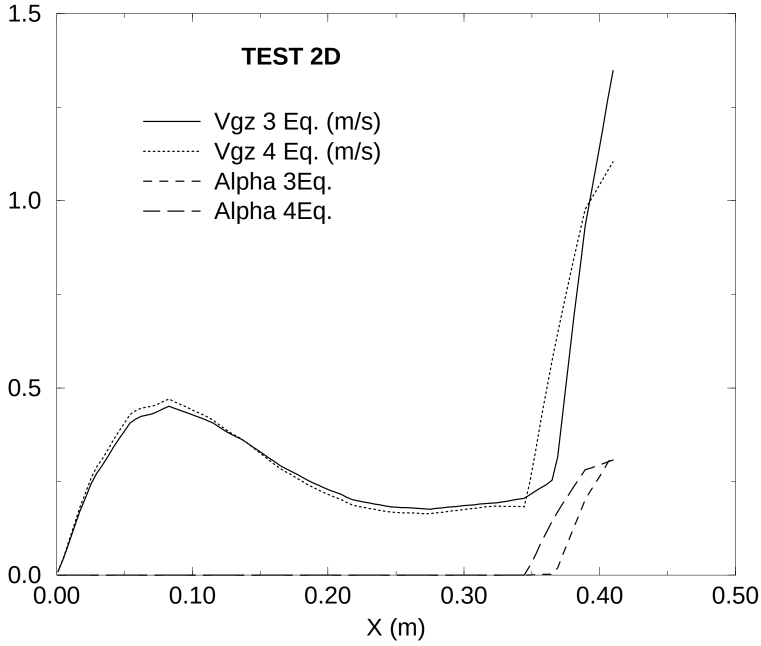

Fig. B.4. Two dimensional gas velocity profile at z=0.13m

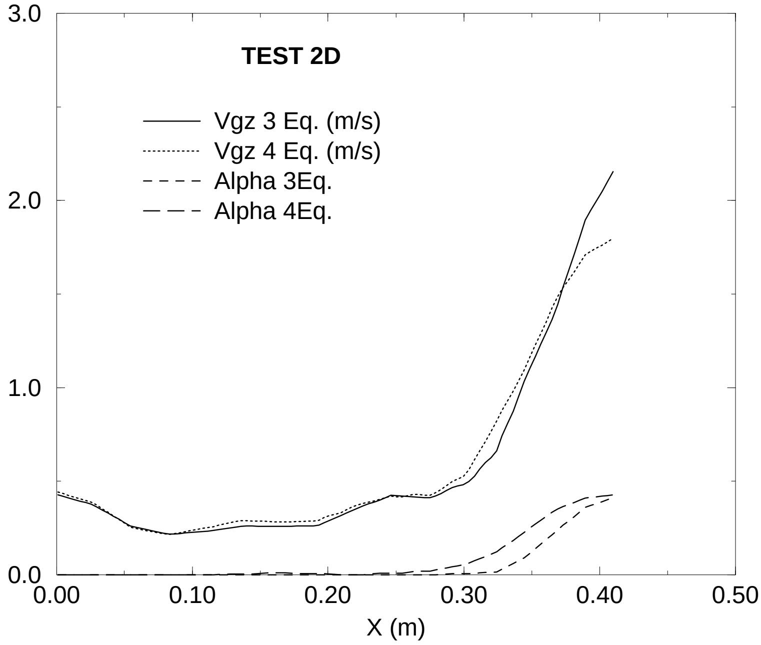

Fig. B.5. Two dimensional gas velocity profile at z=0.38m

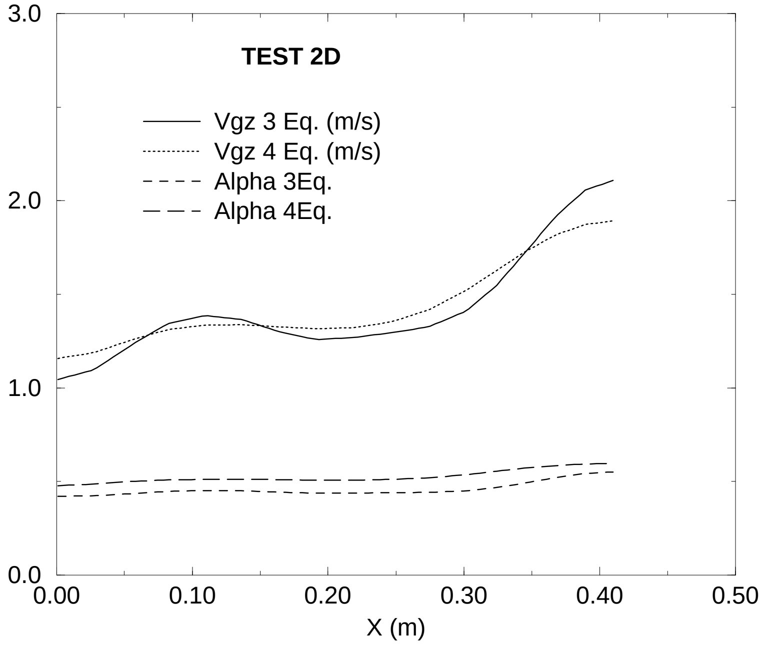

Fig. B.6. Two dimensional gas velocity profile at z=0.75m

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