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An application of parallel computing to the simulation of volcanic eruptions

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Summary. — A parallel code for the simulation of the transient 3D dispersal of volcanic particles produced by explosive eruptions is presented. The model transport equations, based on the multiphase flow theory, describe the atmospheric dynamics of the gas-particle mixture ejected through the volcanic crater. The numerics is based on a finite-volume discretization scheme and a pressure-based iterative non-linear solver suited to compressible multiphase flows. The code has been parallelized by adopting an *ad hoc* domain partitioning scheme that enforces the load balancing. An optimized communication layer has been built over the Message-Passing Interface. The code proved to be remarkably efficient on several high-performance platforms and makes it possible to simulate fully 3D eruptive scenarios on realistic volcano topography.

PACS `02.70.-c` – Computational techniques; simulations.
PACS `47.11.-j` – Computational methods in fluid dynamics.
PACS `91.40.-k` – Volcanology.
PACS `47.27.-i` – Turbulent flows.

1. – Introduction

During explosive eruptions, a mixture of gas and pyroclasts (volcanic particles of various nature) is ejected at high velocity, pressure, and temperature from the volcanic conduit, forming a turbulent volcanic jet. When the jet has exhausted its initial thrust, depending on the efficiency of the turbulent mixing, it can either rise by positive buoyancy to form a buoyant plume or collapse under the action of gravity to form a density current (or pyroclastic flow).

Modelling of these phenomena requires indeed advanced techniques for multiphase flow, sub- and super-sonic flows, turbulence modelling, complex geometries, non-Newtonian rheology, and free-surface stratified flows. In this paper we present a new parallel code [1], named PDAC (Pyroclastic Dispersal Analysis Code), that has been developed on the basis of the multiphase flow model of [2], and that allows to describe the dynamics of the collapse of the volcanic column and the propagation of the related pyroclastic flows in fully 3D conditions.

2. – The physical model

The model transport equations can be expressed by a set of generalized Navier-Stokes equations where the density of each phase is substituted by its *bulk density* (*i.e.* the microscopic density multiplied by the volumetric fraction) and additional terms for interphase momentum and energy exchange are added. For the gas phase and for each species the mass, momentum and enthalpy transport equations write

$$\begin{aligned}
&\frac{\partial}{\partial t}\epsilon_g\rho_g + \boldsymbol{\nabla}\cdot(\epsilon_g\rho_g\mathbf{v}_g) = 0,\\
&\frac{\partial}{\partial t}\epsilon_g\rho_g y_j + \boldsymbol{\nabla}\cdot(\epsilon_g\rho_g y_j\mathbf{v}_g) = 0, \qquad j = \mathrm{H_2O}, \mathrm{CO_2}, \mathrm{air}, \dots,\\
&\rho_g\epsilon_g\frac{\mathrm{d}\mathbf{v}_g}{\mathrm{d}t} = \boldsymbol{\nabla}\mathbf{T}_g + \epsilon_g\rho_g\mathbf{g} - \epsilon_g\boldsymbol{\nabla}P + \sum_{l=1}^{n}\mathbf{M}_{gl},\\
&\rho_g\epsilon_g\frac{\mathrm{d}h_g}{\mathrm{d}t} = -\boldsymbol{\nabla}\epsilon_g\mathbf{q}_g + \epsilon_g\frac{\mathrm{d}P}{\mathrm{d}t} + \sum_{l=1}^{n}I_{gl},
\end{aligned}$$

whereas for each particulate phase

$$\begin{aligned}
&\frac{\partial}{\partial t}\epsilon_s\rho_s + \boldsymbol{\nabla}\cdot(\epsilon_s\rho_s\mathbf{v}_s) = 0, \qquad s = 1, 2, \dots, n,\\
&\rho_s\epsilon_s\frac{\mathrm{d}\mathbf{v}_s}{\mathrm{d}t} = \boldsymbol{\nabla}\mathbf{T}_s + \epsilon_s\rho_s\mathbf{g} - \epsilon_s\boldsymbol{\nabla}P - \mathbf{M}_{gl} + \sum_{l=1}^{n}\mathbf{M}_{sl}, \qquad s = 1, 2, \dots, n,\\
&\rho_s\epsilon_s\frac{\mathrm{d}h_s}{\mathrm{d}t} = -\boldsymbol{\nabla}\epsilon_s\mathbf{q}_s - I_{gs}, \qquad s = 1, 2, \dots, n,
\end{aligned}$$

where ϵ is the volumetric fraction, ρ the density, y the mass fraction of each gas component, $\mathbf{v}$ the velocity, $\mathbf{T}$ the stress tensor, h the enthalpy, $\mathbf{g}$ the gravity acceleration, $\mathbf{M}$ the interphase drag, P the pressure, $\mathbf{q}$ the heat flux, and I the interphase heat transfer term. $\mathrm{d}/\mathrm{d}t$ respresents the total derivative. Subscripts g, s denote the gas and solid phases, respectively. They constitute a set of $5*(n+1)+(m-1)$ coupled partial differential equations. Gas density and momentum equations are coupled through the gas ideal equation of state, the interphase exchange terms transfer momentum and energy among the different phases, whereas the solid density ρ_s is constant. For a detailed discussion of the multiphase flow model please refer to [2] and [1].

3. – Numerics and parallelization strategy

The transport equations are discretized by adopting a finite-volume approach on a orthogonal, non-uniform mesh. In 2D, the mesh can represent a poloidal half-plane in cylindrical coordinates or a Cartesian slice. In 3D, only the Cartesian equations are solved. Diffusive gradients are computed by a second-order, centered scheme, whereas the convective gradients are computed by adopting different second-order upwind methods

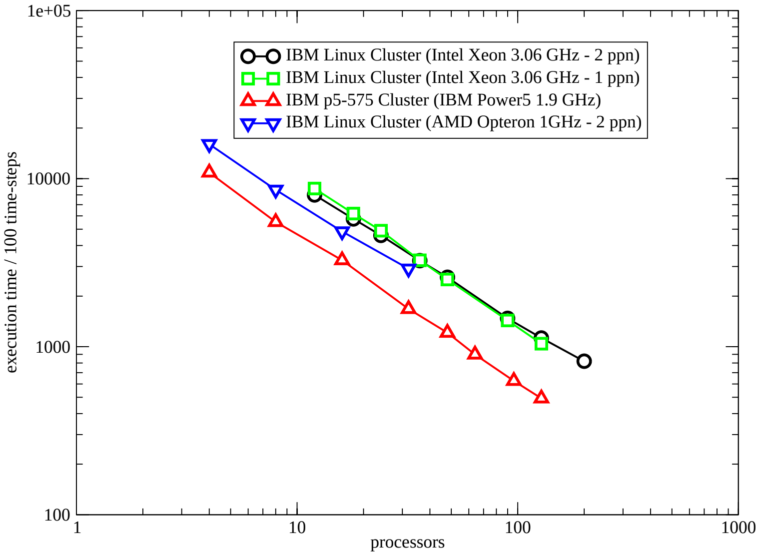

Fig. 1. – Comparison between the execution time of three different platforms as a function of the number of processors.

(MUSCL flux reconstruction). The system of the discretized equations is then solved by a parallel SOR iterative method. The non-linear mass and momentum coupling in each cell is solved by a pressure-based predictor-corrector method suited for compressible flows. The volcano topography is described by using the *immersed boundary* technique [3].

The parallelization of the numerical algorithm is based on the SPMD (Single Program Multiple Data) paradigm and it is implemented through the MPI interface. The computational domain is decomposed into sub-domains of nearly equal size, in order to balance the computational load, and each processor is charged of the solution of the model equations in one sub-domain. Three domain-decomposition criteria are implemented in PDAC through an automatic procedure that holds for any number of processors.

The parallel code has been ported and tested on different modern parallel computers, representative of a large part of the architectures that the supercomputing market offers today. These includes the IBM-Xeon Linux Cluster and the IBM p5-575 Cluster available at CINECA, and the IBM-Opteron Linux Cluster available at INGV Pisa. An exemplificative plot of the execution time as a function of the number of processors is represented in fig. 1 for the three different platforms and a block partitioning of the domain.

4. – Applications

The new 3D multiphase flow model has been applied to the simulation of column collapse scenarios and pyroclastic flow propagation at Vesuvius [4, 5] as well as to the modelling of volcanic blasts (see [6] for an application to the Boxing Day event of the Soufriere Hills volcano, Montserrat). As an example, fig. 2 shows the flow pattern characterizing the collapsing regime of a volcanic column. Simulation results clearly illustrated the unsteady and asymmetric regime of the transitional column able to effectively split

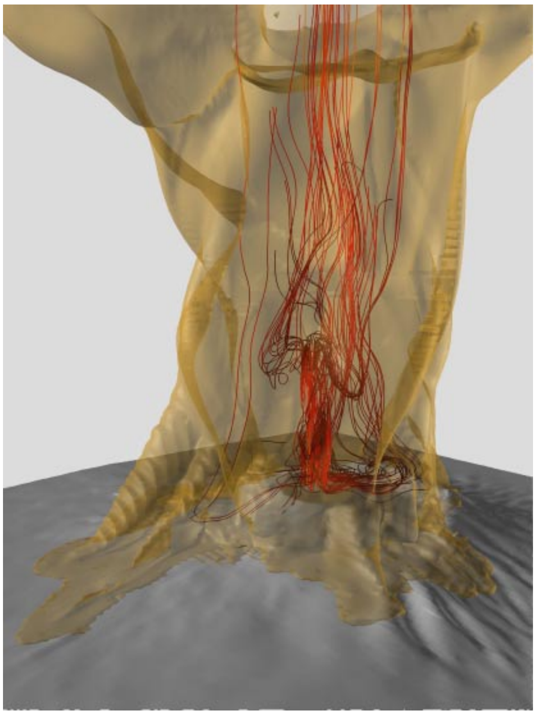

Fig. 2. – (Colour on-line) 3D view of the complex flow pattern characterizing the collapse of the volcanic column. The brown isosurface corresponds to a total volume concentration of volcanic particles of 10^{-6}. The red lines shown illustrate the flow streamlines followed by the inner portion of the column.

the erupted mass among collapsing and convective streams. Results can also be used in the quantification of the hazardous actions associated to these explosive phenomena as well as to the assessment of their impact and risk for the nearby regions.

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