Scalability of OpenFOAM for Simulations of a Novel Electromagnetic Stirrer for Steel Casting

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Abstract - *In this work, custom codes were developed for HPC-based magnetohydrodynamics (MHD) simulations, enabling the design of a dedicated electromagnetic stirrer (EMS) for the electric arc furnaces (EAF). The fluid-dynamics of liquid steel within the EAF under the effect of electromagnetic stirring has been studied under different simulation parameters. We performed parallel simulations using an OpenFOAM solver and other related programs on IBM-FERMI (a PRACE Tier-0 system) at CINECA, Italy. We realized performance analysis for the current sequential version and updated parallel versions of the code via extensive simulations. We present and discuss the results of the scalability analysis of the specific codes using two different domain decomposition methods including simple and hierarchic.*

Keywords: HPC, scalability, OpenFOAM, steel casting, magnetohydrodynamics simulations

1 Introduction

The use of state-of-the-art electromagnetic stirrers (EMSs) for steel quality improvement represents a well-established practice in the steelmaking industry ([1], [2]). Besides their employment in steel continuous casting, dedicated EMS can be designed to improve the performance of the electric arc furnace (EAF), where metal scrap is melted at the very first stage of the steel casting process. A state-of-the-art overview of the applications of electromagnetic machines in the steelmaking industry is given in [2]. Numerical simulations of the effects of electromagnetic fields on liquid metals can be performed by various Computational Fluid Dynamics (CFD) codes, including OpenFOAM [3], which solve the equations of Magneto-Hydro-Dynamics (MHD) models. A general review of possible solutions is given by Murawski [4]. More recently, swirl flow velocities are compared in the presence and absence of solidification for the mould EMS system simulations (see Ren et al. [5]). Moreover, a cellular-automaton-finite-element method was used to simulate the solidification structure of a continuous casting large round billet to examine the effect of mold electromagnetic stirring (see Tao et al. [6]). Furthermore, a variational multiscale algorithm was employed to simulate the liquid steel flow in a non-industrial EMS application in order to study the small scale turbulences in [7]. In order to design highly customized EMSs, dedicated codes for MHD simulations need to be implemented.

It is important to conduct research including HPC-based MHD simulations to design a new EMS dedicated to the casting of large blooms. The very first stage of the casting process is the melting of metal scrap into the EAF. Optimal steel melting has a critical impact on the efficiency of the overall casting process both in terms of energy efficiency, costs optimization and productivity. Employment of electromagnetic stirring in the EAF significantly improves the EAF performance by providing several benefits, including improved homogenization of the liquid bath and reduced furnace wear.

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The goal of this paper is to conduct HPC-based simulations of the fluid dynamics of liquid steel in the EAF under the effect of electromagnetic stirring. Due to the complexity of the multi-physical system under study, very fine discretization in terms of geometry will be required. The use of HPC and the possibility to take advantage of specialized expertise is therefore key to meet this industrial challenge.

The remainder of this paper is organised as follows: Section 2 presents methodology and results. Section 3 concludes this work.

2 Methodology and results

EMS design has been performed following an iterative, multiple-simulation process including: 1) analysis of the geometrical constraints, 2) calculation of the EM performance, 3) fluid dynamic simulation 4) parameter calibration, 5) iteration of steps 2 to 4 until the required EM performance is achieved.

The project partners at ITU (Duran, Hundur and Tuncel) have prepared sequential job submit scripts and parallel job submit scripts to compile and run OpenFOAM with mathematical operators such as turbulence models and various mesh operators and the solver, and also to execute other related programs on IBM-FERMI at CINECA, Italy. They guided Ergolines for performance and scalability of the codes on HPC system.

Fig. 1a: EAF geometry and mesh (top view).

Fig. 1b: EAF geometry and mesh (bottom view).

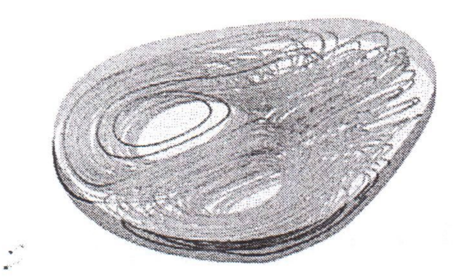

Fig. 1c: Fluid-dynamic simulation: velocity field displayed as flux lines (top view).

Fig. 1d: Fluid-dynamic simulation: velocity field displayed as vector field (bottom view).

The fluid-dynamics of liquid steel in an electric arc furnace under the effect of electromagnetic stirring has been studied by means of HPC-based numerical simulations. The geometry, mesh and fluid dynamics of the system under study are represented in Figures 1a-1d. The velocity field generated by the EMS, which is located under the EAF, is also shown.

The magnetic field produced by the stirrer and the force field induced into the steel has been computed by means of Comsol Multiphysics in order to calculate the initial conditions for the fluid-dynamic simulations. The stationary magnetic and force fields have then been used as initial conditions for the fluid dynamic simulations, carried out in OpenFOAM code (C++, MPI) where OpenFOAM (see [3]) is an open source CFD toolbox. A series of fluid dynamic simulations has been performed by considering a stationary magnetic field. A mesh of 3 million elements was used. Ergolines' proprietary solver, implemented in OpenFOAM, has been compiled on the CINECA FERMI supercomputer. GNU 4.4.6 C++ compiler has been used because the related libraries were compiled via GNU by CINECA. Specifically, in order to simulate the effects of electromagnetic stirring on liquid steel, a dedicated customization of Ergolines' current OpenFOAM code has been implemented so as to couple Electromagnetism with Fluid Dynamics. The simulations in this work are obtained using the OpenFOAM 2.1.1.

In order to better assess how parallelisation improves computational performance, the simulations have been carried out by considering an increasing number of processors. All the simulations were run over 200 iterations: in fact, this figure represents a good trade-off between computational times and statistics, since it produces enough data to carry out a sound statistical analysis while maintaining at the same time an acceptable computational time.

In addition, two different domain decomposition methods have been compared:

- The "simple" method, which generates a mesh where the number of elements per unit volume is in general not the same for all the elements;
- The "hierarchical" method, which generates a mesh where the number of elements per unit volume is constant in the whole domain. This approach enables to efficiently distribute the computational load between the cores.

While the first approach is best suited for simple geometries, the latter one is more convenient when dealing with complex domains. We observe that the simple decomposition is not a suitable strategy for the case using 256 cores possibly due to the unbalanced computational load distribution in Table 1.

The results of the simulations are reported in Table 1, where performance is quantified in terms of speed-up and computational time. The BlueGene/Q (FERMI) configuration (see [8]) is made of 10 racks such as 2 racks having 16 I/O nodes per rack, implying a minimum job allocation of 64 nodes (1024 cores) and 8 racks having 8 I/O nodes per rack, implying a minimum job allocation of 128 nodes (2048 cores). In other words, each node contains 16 cores.

Figure 2.a shows the measured speed-up as a function of the number of cores used. The ideal trend is linear and it is displayed as a green line for comparison. The blue and red lines represent the measured trends based on the hierarchic and simple methods, respectively.

Table 1. Data displayed in Figures 2 and 3. Legend: *# of nodes*: number of nodes allocated on CINECA FERMI (minimum 64). Each node has 16 cores at most. *# of cores*: number of cores used in the simulation. *# of iterations*: number of iterations. *Decomposition*: domain decomposition methos and strategy (different strategies were used for the same method). *Computation time*: time of the simulation (seconds). *Speed-up*: speed-up as a function of the number of cores, calculated as the ratio of the time with "n" cores over the time with 20 cores (20 cores has been considered as the normalization factor).

# of nodes	# of cores	# of iteration	Decomposition	Computational time (s)	Speed-up
64	256	200	not suitable with simple decomposition strategy		
64	128	200	simple 8x4x4	9520	3.04
64	64	200	simple 4x4x4	15907	1.82
64	**20**	**200**	**simple 2x2x5**	**28988**	**1.00**
256	1024	200	hierarc. 32x4x8 xzy	1241	25.96
256	1024	200	hierarc. 16x8x8 xzy	1277	25.23
128	1024	200	hierarc. 16x8x8 xzy	1304	24.71
128	1000	200	hierarc. 10x10x10 xzy	1247	25.84
128	900	200	hierarc. 10x10x9 xzy	1231	26.18
128	800	200	hierarc. 10x10x8 xzy	1254	25.70
128	600	200	hierarc. 10x10x6 xzy	1412	22.82
64	512	200	hierarc. 8x8x8 xzy	1477	21.82
64	512	200	hierarc. 16x4x8 xzy	1544	20.87
64	400	200	hierarc. 10x10x4 xzy	2005	16.07
64	256	200	hierarc. 8x4x8 xzy	2830	11.39
64	128	200	hierarc. 8x4x4 xzy	5479	5.88
64	64	200	hierarc. 8x2x4 xzy	10613	3.04
64	**20**	**200**	**hierarc. 5x2x2 xzy**	**32222**	**1.00**

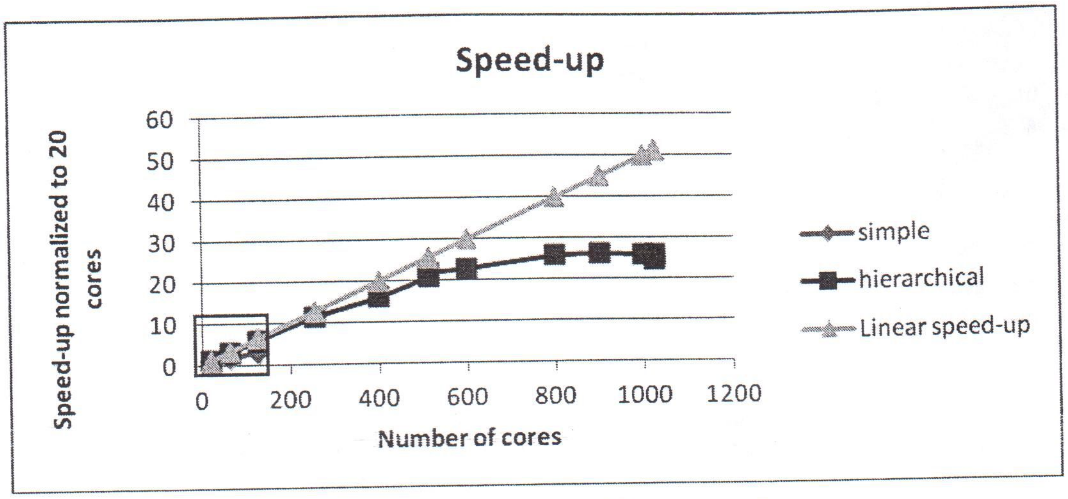

Fig. 2a: Speed-up as a function of the number of cores.

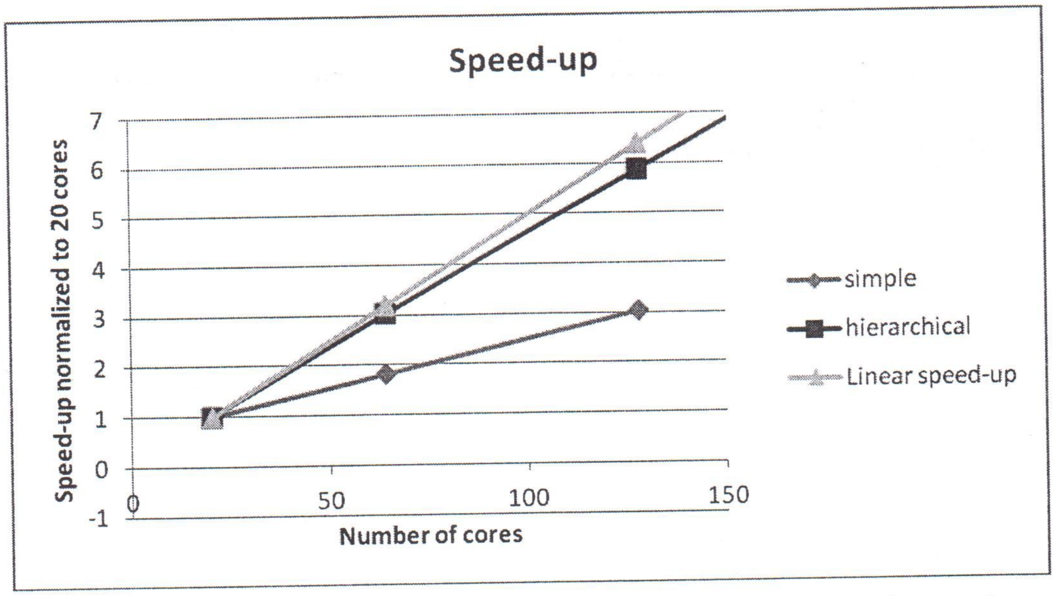

Fig. 2b: Zoom on the region of the graph in Fig. 2a enclosed in a red rectangle: linear regime.

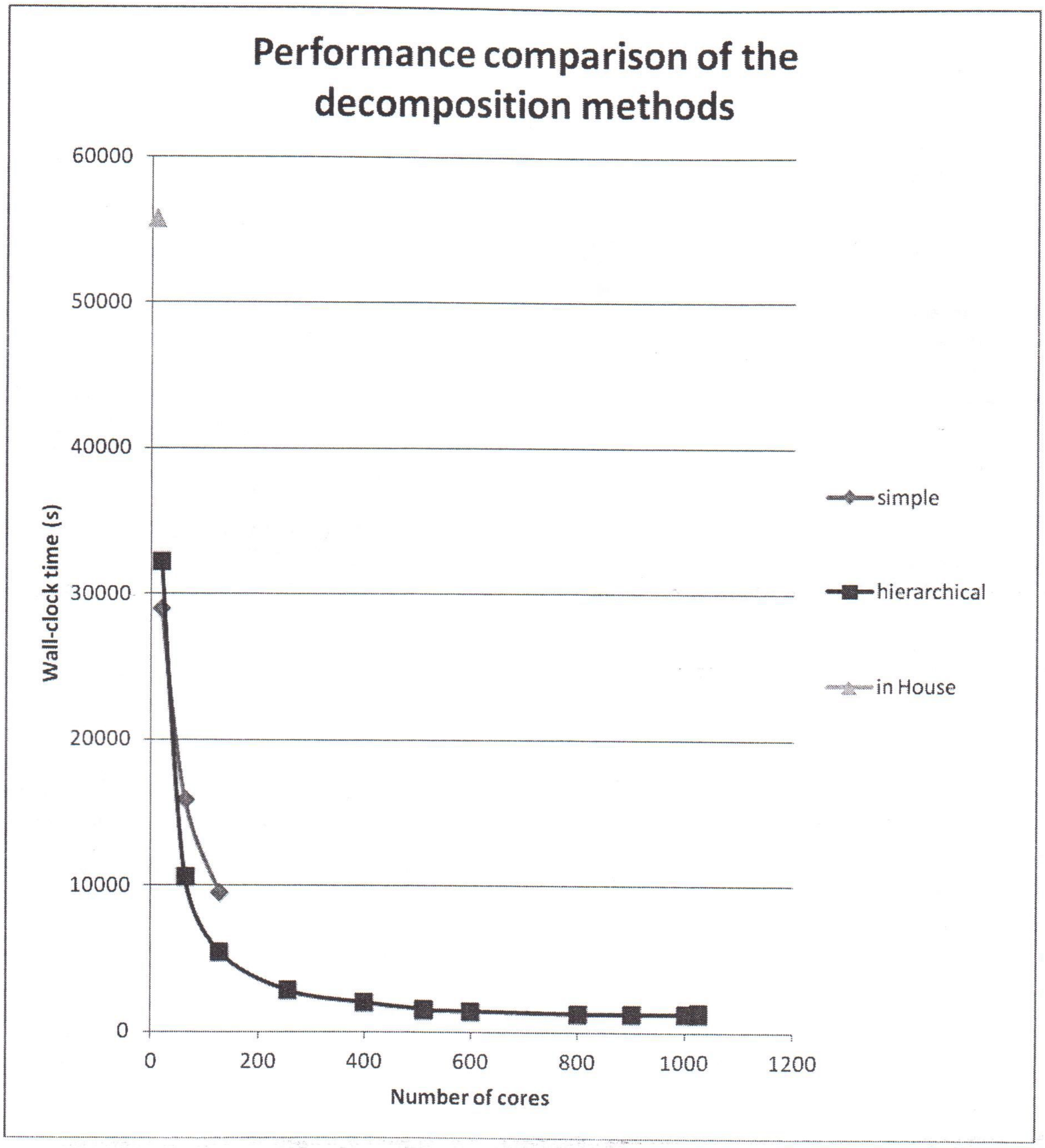

Fig. 3: Wall-clock time as a function of the number of cores.

Figure 2.a displays almost a linear speed-up till 512 cores. Part of the linear region is enlarged in Figure 2.b, which shows the superior performance of the hierarchic decomposition, close to the ideal trend, with respect to the simple method. In fact, since the shape of the domain representing the furnace is quite complex, the hierarchic decomposition enables to distribute the mesh elements and computational load much more efficiently than the simple method. In addition, the simple method fails to decompose the domain if more than 128 cores are used. Based on this result, in all the successive simulations only the hierarchical method was used.

After 512 cores, the speed-up growth-rate gradually decreases and saturation is reached. When a large number of cores are used, the number of elements per core decreases, reducing the computational time, but the communication overhead dominates because more cores need to communicate with each other. Since this figure is characteristic of the system, it does not improve so much by increasing the number of cores, thus causing the speed-up to saturate. Moreover, we observe a gradual speed-up up to 1024 cores with oscillations depending on the decomposition and the memory usage of each core in Table 1. For example, the simulation took 1241 seconds with the hierarchical decomposition mesh of 32x4x8 and 1024 cores as having advantage where 4 cores are used per node instead of 8 cores per node so that a larger memory can be provided.

3 Conclusions

We conducted research and prepared codes/scripts for HPC-based magnetohydrodynamics simulations for designing an electromagnetic stirrer. We performed parallel simulations using the OpenFOAM, solver and other related programs on IBM-FERMI at CINECA. We obtained that the solver with hierarchical decomposition method scales for a mesh domain having 3000 K elements, on FERMI, CINECA. We observed almost a linear speed-up up to 512 cores and then a gradual speed-up up to 1024 cores. Moreover, the matrices having larger order coming from the finer meshes may require a higher saturation point for the optimal minimum number of cores (see [9]). Thus, the code is suitable for the BlueGene/Q (FERMI) system.

The fluid-dynamics of liquid steel in an electric arc furnace under the effect of electromagnetic stirring has been studied by means of HPC-based numerical simulations. The velocity field was generated by the EMS.

As a conclusion, the use of HPC for steel casting provided a dramatic advantage and enabled to carry out an extensive analysis of the fluid-dynamic of the liquid steel in the furnace under the influence of electromagnetic stirring, providing key information for EMS design and industrialization.

Acknowledgements

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4 References

[1] Norbert Vogl, Hans-Jürgen Odenthall, and Markus Reifferscheid, Fluid flow in continuous casting affected by electromagnetic fields, 6th International Congress on Science and Technology of Steelmaking, Beijing, May 2015.

[2] Brian G. Thomas and Rajneesh Chaudhary, State of the art in electromagnetic flow control in continuous casting of steel slabs: Modelling and plant validation, 6th Int. Conference on Electromagnetic Processing of Materials EPM 2009, Oct. 2009.

[3] OpenFOAM main site, http://www.openfoam.com

[4] Kris Murawski, Numerical solutions of magnetohydrodynamics equations, Bulletin of the Polish Academy of Sciences, Technical Sciences, 59(2), 2011.

[5] B-Z. Ren, D-F. Chen, H-D. Wang, M-J. Long, and Z-W. Han, Numerical simulation of fluid flow and solidification in bloom continuous casting mould with electromagnetic stirring, Ironmaking & Steelmaking, 42(6), 401–408, 2015.

[6] Tao Sun, Feng Yue, Hua-jie Wu, Chun Guo, and Ying Li, and Zhong-cun Ma, Solidification structure of continuous casting large round billets under mold electromagnetic stirring, Journal of Iron and Steel Research, International, 23(4), 329–337, 2016.

[7] Marioni Luca, Jose Alves, François Bay, and Elie Hachem, Effect of m-ems on in-mould transient flow during continuous casting, the Proceedings of Int. Conference on Heating by Electromagnetic Sources, Italy, May 2016.

[8] http://www.cineca.it/en/content/fermi-bgq

[9] Ahmet Duran, M. Serdar Celebi, Senol Piskin, and Mehmet Tuncel, Scalability of OpenFOAM for bio-medical flow simulations, Journal of Supercomputing, 71(3), 938–951, 2015.