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Partnership for Advanced Computing in Europe

SHAPE Project *Ergolines - ITU Partnership:*

HPC-based Design of a Novel Electromagnetic Stirrer for Steel Casting

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Abstract

Ergolines, an Italian SME expert in the design of electromagnetic stirrers for metal casting, and the project partners at ITU collaborated in a European research project under the EU's Horizon 2020 Research and Innovation Programme, in particular under the SME HPC Adoption Programme in Europe (SHAPE*)*, organized within the PRACE Research Infrastructure. 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). We performed parallel simulations using an OpenFOAM solver and other related programs on IBM-FERMI (a PRACE Tier-0 system) at CINECA, Italy. The fluid-dynamics of liquid steel within the EAF under the effect of electromagnetic stirring has been studied under different simulation parameters.

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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 also 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 magnetohydrodynamics (MHD) models. A general review of possible solutions is given by Murawski [4]. In order to design highly customized EMSs, dedicated codes for MHD simulations need to be implemented.

In this project, electromagnetic stirring through the EAF was imitated in parallel MHD simulations via developing custom codes in order to achieve optimized costs and productivity. The remainder of this paper is organised as follows: In Section 2, the project partners are presented. In Section 3, the project and its goals are described. In Section 4, the project activities, methodology and results are showed. In Section 5, the cooperation

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between PRACE and SME is explained. In Section 6, the benefits for the SME are discussed. Section 7 concludes this work and provides the lessons learned.

2. Project partners:

- ***End User (SME): Ergolines***
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  - Cristiano Persi, Ergolines s.r.l., Mechanical Engineer, cristiano.persi@ergolines.it
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  - Mehmet Tuncel, Istanbul Technical University, Mathematical Engineering, Computational Science and Engineering.

Ergolines' Company Profile

Ergolines s.r.l. is an Italian SME expert in the design and development of advanced technologies for process control in metal casting and foundry. Established in 1998, Ergolines is based in Area Science Park, Trieste (Italy), one of the most important multi-sector Technological and Scientific Parks in Europe. Their mission is to satisfy specific process requirements and to establish a durable technological and strategic partnership with their customers.

Ergolines core business is represented by the electromagnetic stirrers, special electrical machines used in various sections of continuous steel casting to minimize surface and internal defects of cast products and to increase productivity. Other innovative products for the steel industry include sensors for mold level control, breakout prediction, mold oscillation measurement and ladle-to-tundish slag carry-over monitoring systems. To guarantee highly reliable results, the Ergolines team has developed a new design and simulation software based on electromagnetic, fluid-dynamic and thermodynamic analysis. These specific tools allow the designers to accurately predict the influences caused by variations in electric parameters (e.g. current and/or frequency) and process parameters (e.g. casting speed, type of entry-nozzle, etc.).

The philosophy that makes Ergolines distinguished in its market is its custom-made approach, meaning extreme design flexibility aimed at satisfying the specific engineering requirements of each individual customer, thus offering a technological and strategic partnership. The competitiveness of the company relies on its focus on product customization and growing investment in research and innovation.

Istanbul Technical University

Istanbul Technical University (ITU) is a prominent institution of higher technical education in Turkey. It was established in 1773 and has the largest graduate school in Turkey. Of ITU's five campuses, the main campus is located at Ayazaga, a recently developed business area. With a history stretching back over 243 years, providing technical education within a modern educational environment and strong academic staff, ITU is strongly identified with science and engineering education in Turkey. ITU has participated in all PRACE projects since the beginning.

3. Description of the project and its goals

The overall goal of the project is conducting dedicated research and 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. The goal of the project 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.

4. Description of the work performed, results obtained, resources used

Project Activities

The project activities have been organised into four different phases:

- Porting: deploy and run the code on the BlueGene/Q (FERMI) (a PRACE Tier-0 system) at CINECA, Italy (see [5])
- Profiling: quantification of the computational time spent in each building block of the code
- Conducting initial simulations and parameter optimization: EMS design has been 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 optimization, 5) iteration of steps 2 to 4 until the required EM performance is achieved.
- Benchmarking: performance analysis for the current version and updated versions of the code via extensive simulations.

Methodology and Results

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 figure 1a-1d. The velocity field generated by the EMS, which is located under the EAF, is also shown.

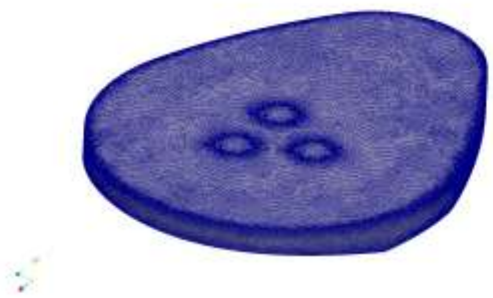

Fig. 1a: EAF geometry and mesh (top view).

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).

In order to calculate the initial conditions for the fluid-dynamic simulations, the magnetic field produced by the stirrer and the force field induced into the steel has been computed by means of Comsol Multiphysics. 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 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 has been carried out by considering an increasing number of cores. 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.

# 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**

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).

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 [5]) 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.

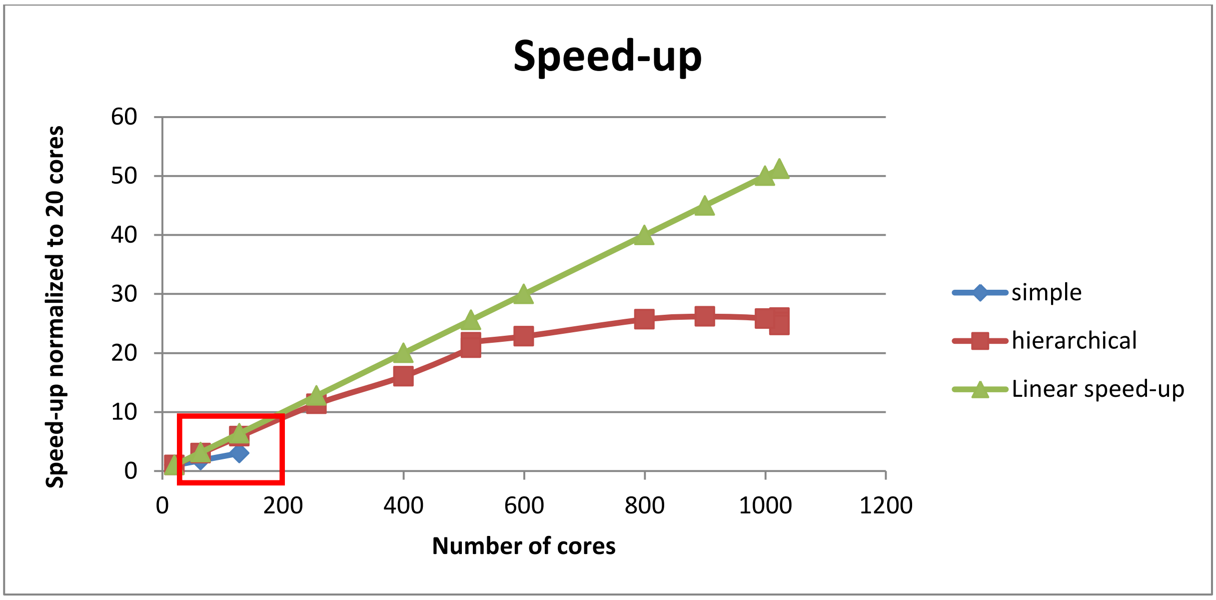

Fig. 2a. Speed-up as a function of the number of cores.

Speed-up saturation takes place if more than 500 cores are used.

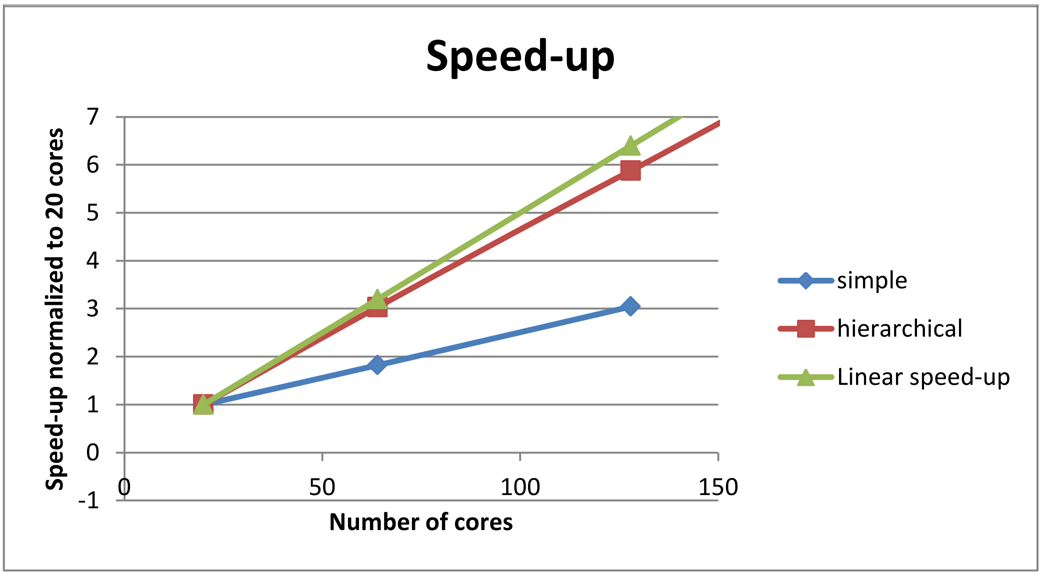

Fig. 2b: Zoom on the region of the graph in Fig. 2a enclosed in a red rectangle: linear regime.

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. The graph shows a linear trend if less than 500 cores are considered. 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.

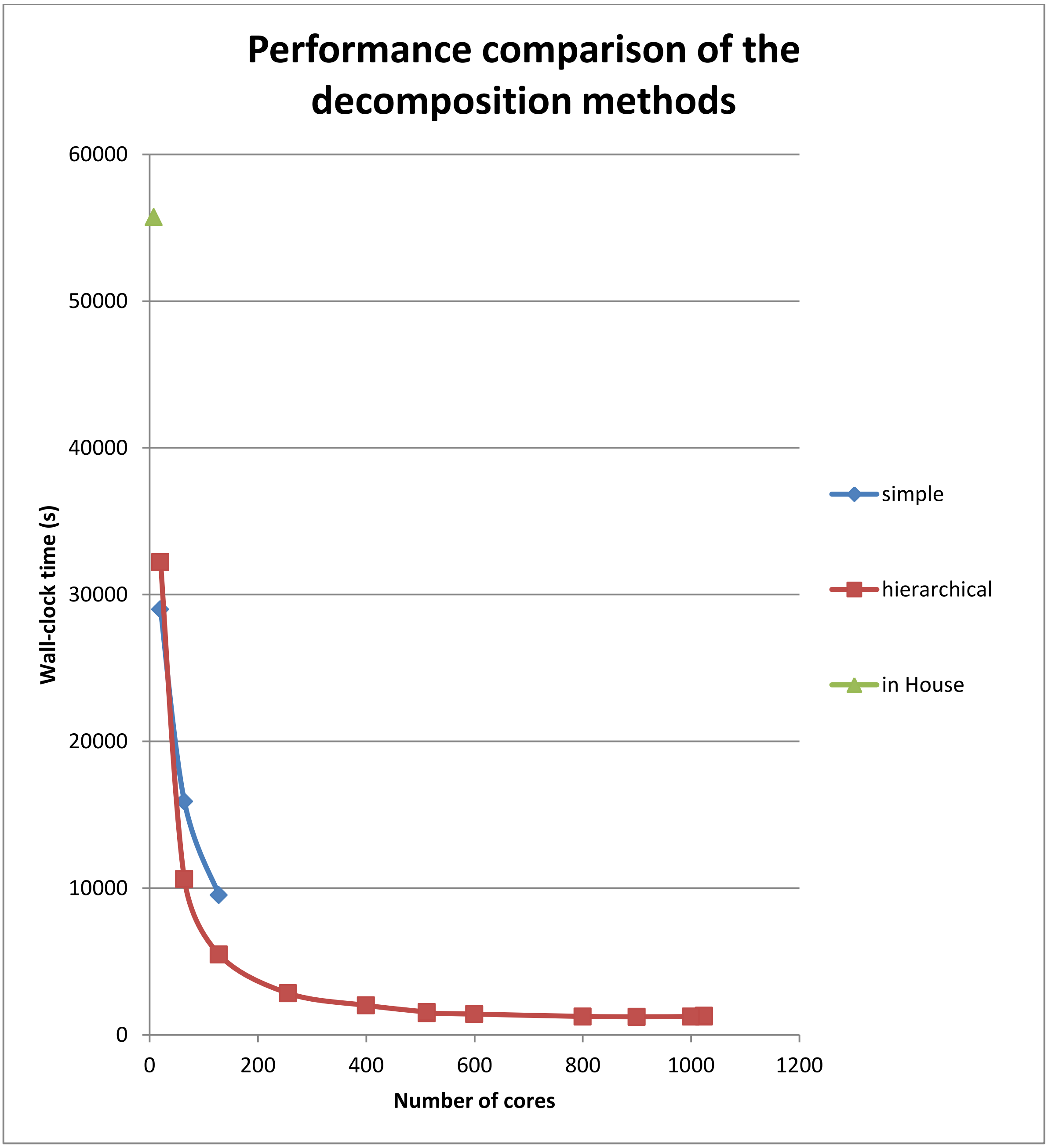

Fig. 3. Wall-clock time as a function of the number of cores.

If more than 500 cores are employed, the speed-up growth-rate gradually decreases until saturation is reached. The saturation is explained as follows: when a large number of cores are used, the number of elements per core decreases, reducing the computational time, but, on the other hand, the bottleneck is represented by the time required by the different cores 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 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.

5. Cooperation between PRACE and the SME

The project partners have prepared a detailed workplan to realize the HPC-based project. The project partners at ITU were awarded to access to IBM-FERMI at CINECA through their Project 2010PA3012 "Parameter Optimization and Evaluating OpenFOAM Simulations for Magnetohydrodynamics" under the 21st Call for PRACE Preparatory Access call Type B. The project partners at ITU 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. They have provided the job submit scripts to Ergolines. They provided guidance for performance and scalability improvements of the codes on an HPC system. The project partners prepared this white paper.

6. Benefits for SME

We note how the use of HPC has been crucial to carry out the fluid-dynamic simulations by drastically reducing the computational times. As shown in Figure 3 and Table 1, performing the simulations in-House, on Ergolines' work-stations having 8 cores, required about 15 hours, while running the same calculations on CINECA FERMI took only about 20 minutes with the hierarchical method with 1024 cores. This dramatic advantage 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.

7. 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 [6]). 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.

PRACE and the projects partners at Ergolines s.r.l. and ITU collaborated excellently to complete the project successfully. All parties hope to have the chance to collaborate again in the future.

References

[1] Vogl N., Odenthall H.-J., M. Reifferscheid, Fluid flow in casting affected by electromagnetic fields, 6th International Congress on Science and Technology of Steelmaking, Beijing 12-14 May 2015.

[2] Thomas B. G., Chaudry R, State of the art in electromagnetic flow control in continuous casting of steel slabs: Modelling and plant validation, 6th International Conference on Electromagnetic Processing of Materials EPM 2009, Oct. 19-23, 2009.

[3] OpenFOAM main site, http://www.openfoam.com
[4] Murawski M, Numerical solutions of magnetohydrodynamics equations, Bulletin of The Polish Academy of Sciences, Technical Sciences, Vol.59, No.2, 2011.
[5] http://www.cineca.it/en/content/fermi-bgq
[6] A. Duran, M.S. Celebi, S. Piskin, and M. Tuncel, Scalability of OpenFOAM for bio-medical flow simulations, Journal of Supercomputing, 71(3), 2015, pp. 938-951.

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