Simulation of ancient wind-driven iron smelting furnaces of Sri Lanka

A.A.K. Kumbalathara, D.D. Liyanage, S. Witharana
Department of Mechanical and Manufacturing Engineering
University of Ruhuna
Galle, Sri Lanka
switharana@ieee.org

J.K.A.T. Rajika, M.Narayana, K.C.N.Fernando
Department of Chemical and Process Engineering
University of Moratuwa
Moratuwa, Sri Lanka

***Abstract*- Metal processing industry in Sri Lanka began around 3000BC. Ancient chronicles like Mahavansaya, Thupavansa and Pujavaliya proved the Sri Lanka's history of metal industry. Archaeometallurgical surveys of Sri Lanka have revealed a non-conventional wind-driven iron smelting furnace for the first time in the world. Some of them dated back to third century BC. Replications of iron smelting process have shown the ability of those furnaces to operate and produce high carbon Steel. CFD modeling and simulation is a popular tool to further understand the fluid flow patterns within and surrounding a furnace. This paper discusses the initial steps of modeling and simulation of the total process of iron smelting in the west-facing furnaces situated in Samanalawewa area of Sri Lanka. Main focus of the paper is to analyze the cold flow at 2D and 3D steady state conditions by using the open source OpenFOAM CFD software with over 9million cells for 3D simulation in finite volume method. The results have been compared with a validated simulation on the same furnace using the commercial CFD code Fluent.**

Keywords—Ancient iron smelting; Sri Lanka; CFD; OpenFoam;

I. INTRODUCTION (*HEADING 1*)

Archaeology surveys about history of metallurgical processes in Sri Lanka have found many details. Metal processing industry in Sri Lanka began around 3000BC. Ancient chronicles like Mahavansa, Thupavansa, Pujavaliya, Culavansa, Dhatuvansa, Dipavansa and epigraphs on stones mentions the history of Sri Lankan metal industry [1, 2]. In 10^{th} - 9^{th} century B.C., evidence was found about iron smelting processes in Sri Lanka from Sigiriya and Anuradhapura [3]. Findings from Sigiriya prove the high technology associated with the iron smelting process. Outer surface of sample artifacts found by R. Hadhield et. al [4] had high carbon content. It shows richness of the technology in iron production in Sri Lanka. Among the many places where evidence about iron and Steel production in Sri Lanka were Dehigaha-ala Kanada near Sigiriya, Kiri Oya, and Samanalawewa in Balangoda were of particular importance. These furnaces were both bellow driven and natural draught driven [5]. Archaeological survey further show that, the ancestors had followed several steps in iron smelting [2]; Initial step was to heat-up the furnace using wood, followed by charcoal combustion of 85kg, 90kg and 95kg for three hours in equal time intervals, and finally to fill the furnaces with ore and charcoal mixture and let the reactions occur. Aim of this project is to unveil the hidden technology behind the ancient iron smelting process. Project will be executed in several steps. Firstly CFD simulation is conducted in OpenFOAM in order to catch up with prior studies [6]. Then CFD simulation on combustion and chemical reaction will be conducted. Optimization of the furnace using CFD will follow. Lastly a furnace will be fabricated to optimum conditions obtained in CFD analysis. This paper addresses the first step stated above and simulates the cold flow within and around the iron smelting furnace found in Samanalawewa.

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II. PREVIOUS WORK

An archaeological survey was conducted in 1988, prior to Samanalawewa hydro-electric project in southern foothills of central high lands of Sri Lanka. This survey identified 139 iron-working sites with the evidence of earliest high-carbon steel production in South Asia.77 sites of them later became known west-facing iron smelting sites [7]. This overwhelming evidence of an innovative technology led to an excavation in the area. It was conducted in 1990. Forty one furnaces have been revealed from the excavation. Such furnace is shown in Fig. 1 as follows. These furnaces were positioning on the western edge of the ridge forming an almost continuous line along South-North. Furnace construction with a C-shaped wall with less than 0.5m of height, which ends with two large stones as shown in Fig. 1.A front wall have been situated across two stones with evidence of destruction in each smelt. This front wall consists of a line of reused clay tuyeres at the bottom and with a row of tuyeres at upper level (sees Fig. 1). The revealed unconventional furnace type arouse the necessity to understand the practicality of the furnace operation. In 1998 July, smelting were replicated with five trials. Furnace have been recreated at an

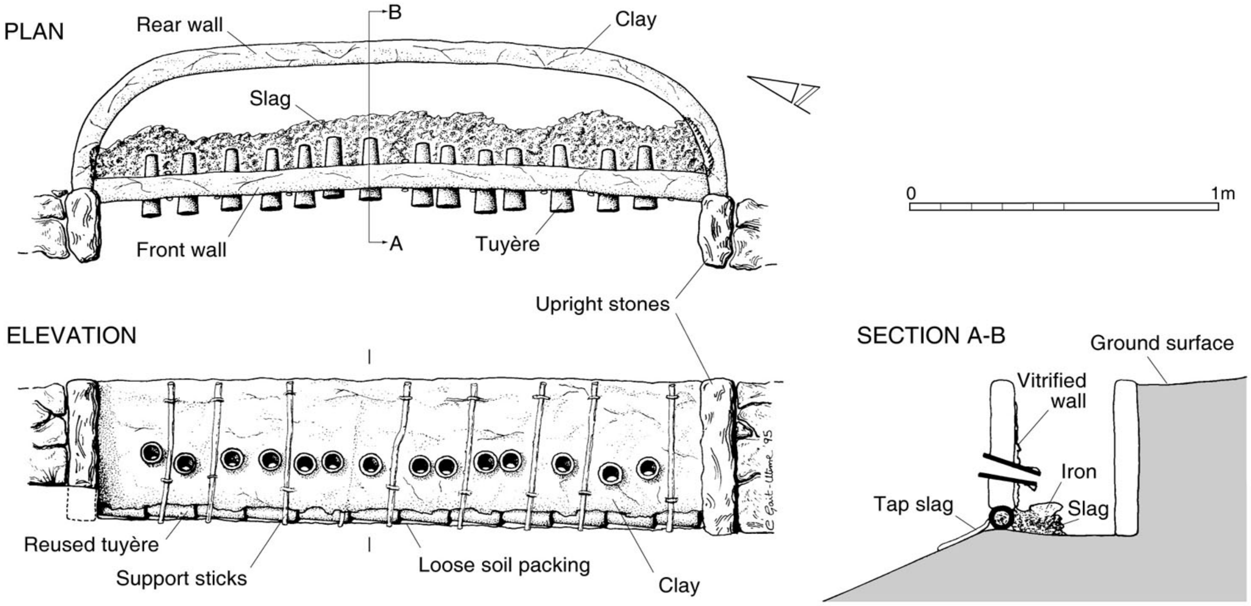

Fig. 1. Ancient iron smelting furnace [6, 7]

TABLE 1 .BASIC MODELING PARAMETERS OF THE FURNACES[6]

Furnace			
Height of front wall	52cm	Thickness of front wall	6.5cm
Height of rear wall	52cm	Thickness of rear wall	10cm
Furnace depth	32.6cm		
Tuyeres			
Inclination angle	20^{0}	Length	19.3cm
Projected into furnace	8.6cm	Cross-sectional area	10.6cm^2
height of tuyeres at front wall	18cm		
west-side of hill			
upwind angle	$\alpha = 20^{0}$		
downwind angle	$\beta = 5^{0}$ or 2.5^{0}		
Physical properties			
Wind speed	0 - 31kmph	porosity of furnace bed	0.35
Temperature of furnace	1200 ^{0}C and 1500 ^{0}C	Equivalent spherical size of solids	57mm

original position of a furnace to obtain the correct orientation. Attention have always paid to recreate exact size and shape of the furnace. Results have confirmed the successful wind utilization for iron smelting, for the first time in the world [7]. This iron smelting operation have been simulated using commercial CFD code Fluent [6]. Main objective of the simulation was to simulate air flow around and inside the furnace with testing the sensitivity of the furnace to various parameters, such as temperature, bed porosity, wind velocity and hillside angles, etc. 2D and 3D steady state simulations have been performed to test cold flow analysis as well as compressible flow. Simulation results have shown that the air flow rates are sufficient to smelt iron with a possibility of producing high carbon iron in 7th-11th century AD. Further, simulation has indicated the importance of the bed resistance to the iron smelting operation. According to Tabor et.al [6], simulation of complete iron smelting process including each and every process has been emphasized.

III. Methodology

All the simulations in this work were carried out using open source CFD software OpenFOAM version 2.3.1 [8]. As discussed previously the main objective of this paper is to take the first step to simulate the ancient wind driven iron smelting furnaces. The simulation data were recruited from [6] which is based on archaeological survey and iron smelting trials conducted with the reconstructed ancient furnaces [7]. Furnace geometry and physical properties are given in Fig. 2, 3 and Table 1.

Due to the 3D nature of the furnace architecture, 2D simulation may not predict reliable results for the system. Therefore a 3D simulation were also carried out. Air flow enters the furnace across the tuyeres. Therefore 2D geometry have been selected across A-B plane shown in Fig. 1. Wind velocity profile was created using the wind data collected from archaeological survey trials. Data shows velocity variations of; 0km/h wind velocities at ground level to 15km/h at 0.5m above, and, 30km/h wind velocity at 2m above the ground level. Fig. 2 shows the geometry of the furnace, surroundings and wind direction.

3D simulation geometry is depicted in Fig. 3. Both flow simulations involve turbulence and therefore Reynold's averaged Navier-Stokes equations have been used for the fluid flow modelling.

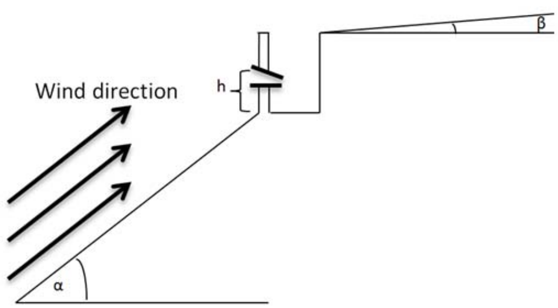

Fig. 2. Geometry of the furnace and surrounding

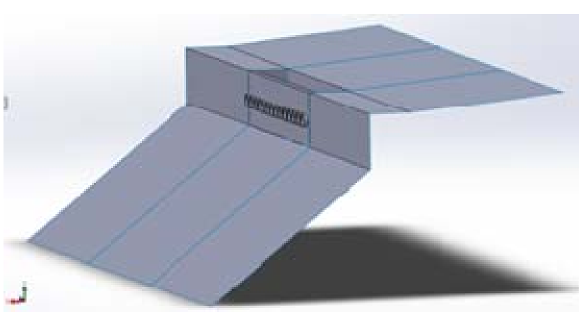

Fig. 3. 3D geometry of the simulation

As [6] have used k-epsilon model, this simulation also carried out using same turbulence model to make a better comparison. Furnace bed is considered as an isotropic porous region where the porosity is assumed according to Table 1.The resistance to the air flow due to the solid bed inside the furnace is modeled using Darcy-Forchheimer equation also referred as Ergun's equation [6]. For the resistance estimation, solid particles considered having an equivalent spherical diameter of 57mm and a porosity of 0.35.

According to the mesh refinement results, 240,000 cells were sufficient to predict mesh independent results for 2D simulation (please refer Fig. 4). Mesh refinement tested from 210,000 cells to 270,000 cells.

A. Computational Fluid Dynamics (CFD)

In this work a CFD simulation model is used to create the iron smelting process which is difficult to replicate with today's conditions. The proper functioning of the furnace can be visualized by using standard CFD models. Standard k-epsilon model is highly validated and very popular among CFD community for turbulence modeling [9]. Bed of the iron smelting furnace is treated as a porous region. Resistance due to porous region is modeled by Darcy-Forchcheimer equation which is used to estimate resistance of fluid flow due to packed beds [10, 11].

This simulation only considers the cold flow through the furnace and it's surrounding. Therefore an incompressible solver in OpenFOAM called "porousSimpleFoam" of OpenFOAM 2.3.1 is used [8]. Table 2 shows the finite volume schemes used for these simulations. Applied boundary types and boundary conditions for the simulation are shown in Table 3.

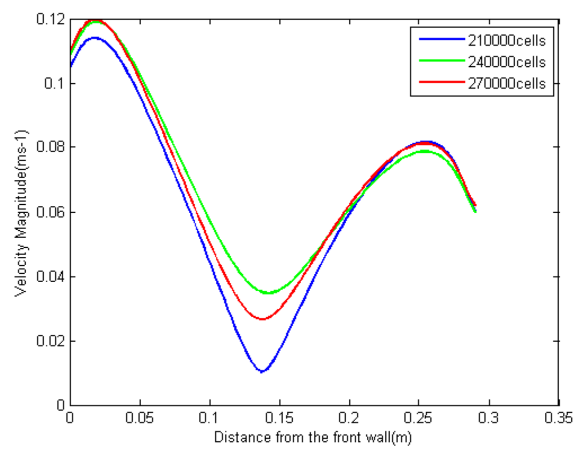

Fig. 4. Velocity magnitudes at furnace outlet with different mesh refinements

IV. Results And Discussion

Results of both simulations are shown and evaluated in this section. Results were validated using traditional bloomer iron air flow rates.

A. 2D Simulation Results

2D flow simulation is carried out only for the S1P4, S1P5 and S1P7 furnaces of [6]. Results are summarized in

Table 4 including total volume flow rate into furnace with 14 tuyeres. According to the results, highest performance in perspective of air flow predicts in S1P7.

B. 3D Simulation Results

As discussed in Methodology, 2D simulation alone cannot be used to determine the flow pattern around and inside the furnace. To compare and contrast with 2D simulation, 3D simulation results of a cutting plane across the tuyeres (see Fig. 1 A-B) are extracted in to Fig. 7. Due to limitations in computational resources, one 3D simulation was conducted with about 2 million cells in the whole domain for furnace S1P7.According to simulation results of both 3D and 2D simulations the flow pattern inside the furnace are similar to the Fig. 6 which is postulated from on-site trials by [9].

3D and 2D simulations have considerable deviations in results among them. For example maximum velocity inside the furnace obtained in 2D simulation was nearly 31% less than that in 3D simulation. Traditional bloomery run on air blast about 0.0667-0.25ms^{-1} [12]. The simulation generated close values to these in the low region (refer Table 3). From the fair convergence of results with mesh refinement at the furnace outlet it is safe to conclude that 2.4×10^5 mesh refinement is accurate enough for 2D simulations.

TABLE 2.FINITE VOLUME SCHEMES USED IN SIMULATION

Term	Scheme
Grad	Gauss linear
Div	Gauss upwind, Gauss linear
Laplacian	Gauss linear corrected
Interpolation	linear
SnGrad	Orthogonal

TABLE 3.BOUNDARY CONDITIONS APPLIED FOR THE SIMULATION DOMAIN

Boundary	Pressure(kgm^{-1}s^{-2})	Velocity(ms^{-1})
inlet	Zero Gradient	Fixed value (non-uniform)
outlet	Fixed Value	inletOutlet
walls	Zero Gradient	Zero(0 0 0)
Porous region walls	Zero Gradient	Slip wall

V. CONCLUSION

Our modelling of thermal and fluid flow behavior around and inside the furnace agrees with previous studies. As it describe in Burnoulli's principle, when the stream lines are getting compact, pressure at that point decreases. This scenario occured above the furnaces. The results of this study clearly explain low pressure region above the furnace. To fill up that vacuum air is sucked from beneath, creating natural ventilation through the furnaces. According to the configuration and locations of iron smelting furnaces in Samanalawewa, it can be shown that naturally driven wind flow is sufficient to fulfill the air blow requirement for iron melting process. This is proved by validating results by flow pattern and having close results with traditional bloomery iron smelting air flows. Therefore, it can conclude that Samanalawewa furnaces were receiving sufficient ventilation for iron smelting which is capable of producing high quality iron. Further CFD modeling and simulation are being conducted to explain the entire iron smelting process that existed in the past.

VI. REFERENCES

[1] R. Solangaarachchi, "History of metallurgy ancient iron smelting," Vidurava, 1997, vol. 19, no. 1, pp. 30–40.

[2] R. Solangaarachchi, "Ancient Iron Smelting Technology and the settlement pattern in the Kiri Oya basing in the dry zone of Sri Lanka," Ph.D. dissertation, University of Florida, pp. 288, 2011.

[3] G. Juleff, "An ancinet wind-powered iron smelting technology in sri lanka," Nature, vol. 379, no. 6560, pp. 60–63.

[4] R.Hadfield, "Sinhalese iron and steel of ancient origin," Journal at red heat into cold water, 1912.

[5] S.U. Deraniyagale and M. Abeyratne, "Radiocarbon Chronology of iron Age and Early Historical Anurdhapura, Sri Lanka: Revised age estimate", South Asian Archaeology 1997.

[6] G.R.Tabor et al., "Computational simulation of air flows through a sri lanka wind-driven furnace," Journal of Archaeological Science, 2005, vol. 32, pp. 753–766.

[7] G. Juleff, "Ancient iron and steel production at samanalawewa", Sabaragama University Journal, 1998, vol. 1, no. 1, pp. 3–9, samanalawewa archaeological project.

[8] OpenFOAM foundation. (2015, March 30). User Guide v2.3.1 [Online].Available: http://foam.sourceforge.net.

[9] H.K.Versteeg and W. Malalasekera, An Introduction to Computational Fluid Dynamics. Pearson Education Limited, 2007, no. 978-0-13-127498-3.

[10] V. A. Jambhekar, "Forchheimer porous-media flow models – numerical investigation and comparison with experimental data," M.S. thesis, University Stuttgart, Germany, 2011.

[11] T. Jurena, "Numerical modelling of grate combustion," Ph.D. dissertation, Brno University of Technology, Faculty of Mechanical Engineering, Institute of Process and Environmental Engineering, 2012.

[12] L. Sauder and S. Williams, "A practical treatise on the smelting and smithing of bloomery iron", Historical Metallurgy, vol 36, no 2, pp. 122-131, 2002.

TABLE 4.2D SIMULATION RESULTS OF FURNACES

Furnace	Alpha angle(^{0})	Beta angle(^{0})	Wind speed(kmh^{-1})	Mean velocity across tuyeres(ms^{-1})	Total volume flow to the furnace(m^3/min)
S1P4	20	5	31	0.0133	0.0118
S1P5	38	5	31	0.0525	0.0467
S1P7	38	2.5	31	0.0531	0.0473

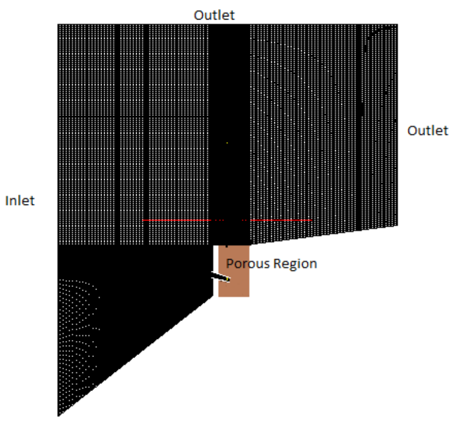

Figure 5a.Simulation domain of the 2D geometry

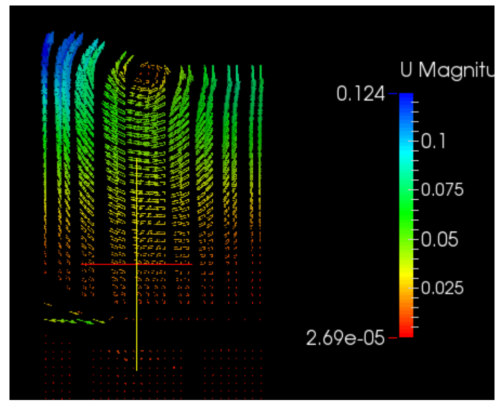

Figure 4b.Velocity inside the furnaces (ms^{-1})

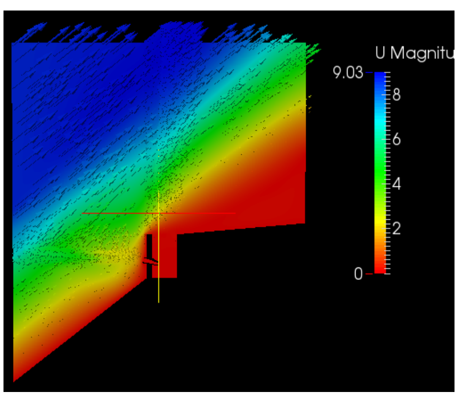

Figure 5c.Velocity distribution across the domain (ms^{-1})

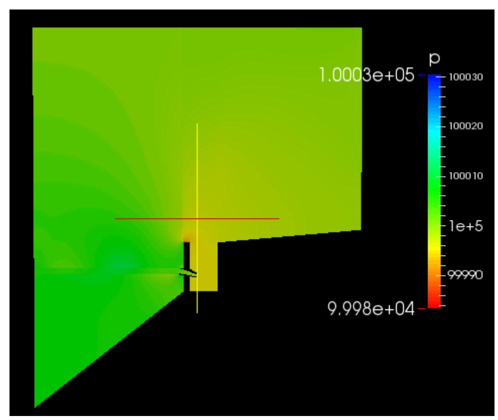

Figure 5d.Pressure distribution across the domain (kgm^{-1}s^{-2})

Fig. 5. Simulation results of 2D approximation

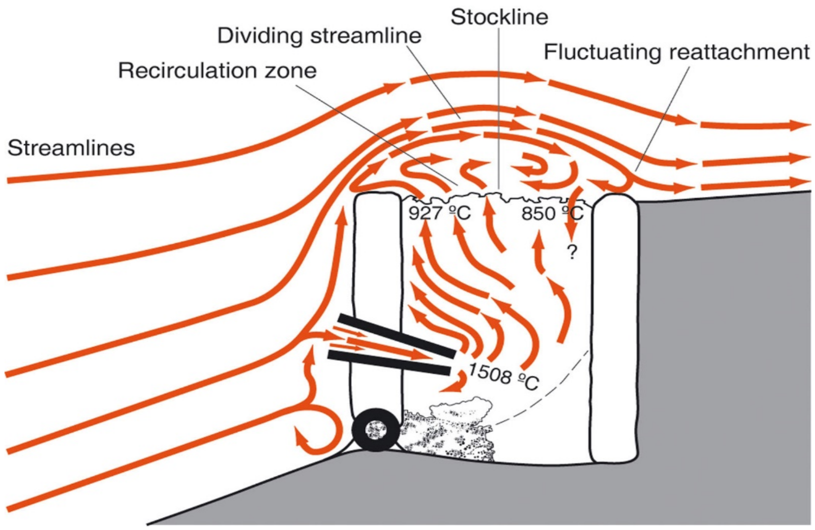

Fig. 6. Expected flow pattern and temperature distribution within the furnace

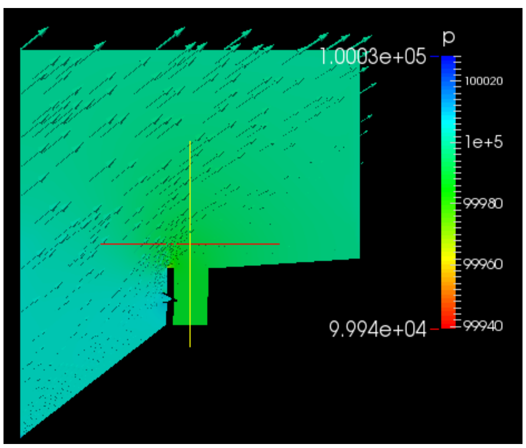

Fig. 7. a. Velocity in a slice of 3D geometry colored by pressure ($kgm^{-1}s^{-2}$)

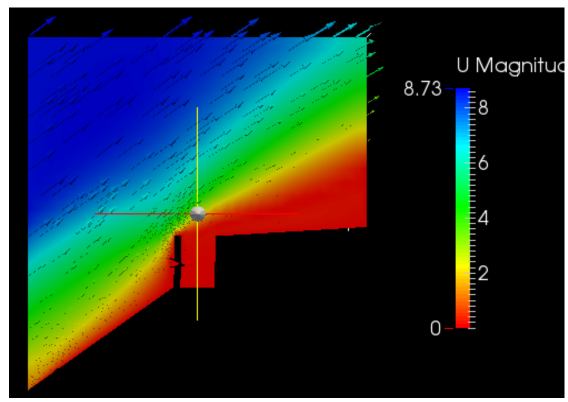

Fig. 7. b. Velocity in a slice of 3D geometry colored by velocity (ms^{-1})

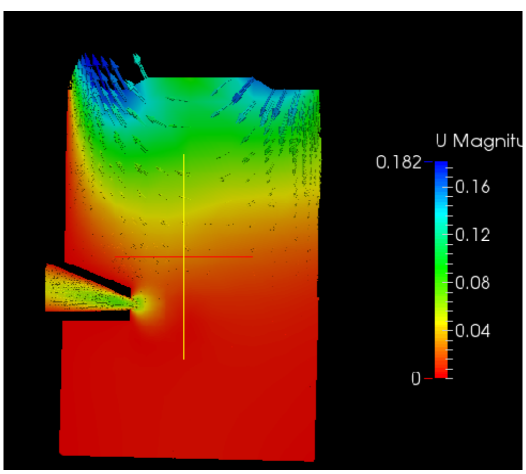

Fig. 7. c. Velocity distribution inside the furnace in a slice of 3D geometry (ms^{-1})

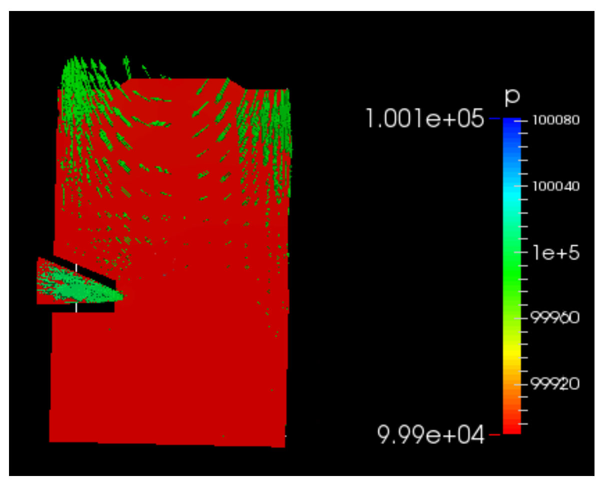

Fig. 7. d. Velocity distribution inside the furnace across a slice of 3D geometry colored by pressure ($kgm^{-1}s^{-2}$)

Fig. 7. 3D simulation results