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Early Iron and Steel production in Sri Lanka:A Scientific Perspective

Prabath Hewageegana
Department of Physics, University of Kelaniya, Kelaniya 11600, Sri Lanka
Corresponding Email: psh@kln.ac.lk

Abstract— ***This work investigates the nature of technological development and the viability of applying an evolutionary approach to the early development of iron production in Sri Lanka. The main objective of this paper is to use modern techniques in the fields of Physics and Engineering to investigate the wind-driven furnace used in early iron and steel producing industry dating to 300 B.C. In order to study the scientific aspects of the furnace, several theoretical calculations were carried out. Some of the crucial parameters and their optimal values are presented.***

Keywords— early iron and steel, wind-powered smelting, high-carbon steels, tuyeres.

I. Introduction

Over 250 archaeological sites and features of Sri Lankan wind-driven furnace were recorded by the 1988 archaeological survey of the *Samanalawewa* area (Fig. 1), in the southern foothills of the Central Highlands of Sri Lanka [1]. The main purpose of the survey was to carry out an in-advance filed study for *Samanalawewa* hydro-electric project. The area was not regarded as archaeologically significant and no sites had been previously recorded. These early furnaces were powered by Monsoon wind and have been dated to 300 B.C. using radiocarbon dating techniques. This proved the Syrian records that once Sri Lankans had the world's best steel technology. These ancient Lankan furnaces might have produced the best quality steel for legendary Damascus swords. It was these steel that was exported to the Middle East. There are records in Syria that the best steel they received was from *"Sivhala"* (Lanka) [1-5].

A proper investigation of the nature of technological development and the viability of applying an evolutionary approach to the early development of iron production shows not only the archaeological interest but also the scientific interest, in particular in the fields of Physics and Engineering. To study the archaeological aspects of the wind-driven furnace, a series of field experiments were carried out in the early 90's in Sri Lanka. The results of these successful trials, using furnaces reconstructed from the archaeological evidence, were fully reported in the journal Nature [6] and established that wind-powered smelting was viable and that these furnaces were capable of producing both low-carbon bloomery iron and, significantly, high-carbon impurity-free steels.

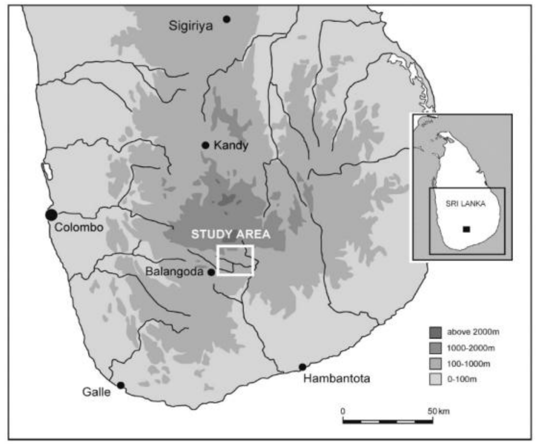

Fig: 1 Map of Sri Lanka marking the Samanalawewa project area.

II. Motivation

The air flows around and through the wind-driven furnace used in early iron and steel production in Sri Lanka has been reported in details [7]. The behaviour of fluids such as air is governed by a set of mathematical equations known as the Navier-Stokes equations, which embody the differential equation of conservation of linear momentum for an incompressible Newtonian fluid with constant properties. Unfortunately, there aren’t very many known analytical solutions available in the literature to this equation. However, only few examples of analytical solutions to this equation for simple (usually infinite) geometries have been found. There most of the terms in the component equations are eliminated and the resulting differential equations are analytically solvable. There are two reasons for this: the equations are complicated, involving five interdependent variables (pressure, three components of velocity and the internal energy), and in addition the equations are non-linear, which also increases the complexity. The Physics behind the success of the Early Iron and Steel production in Sri Lanka have not been discussed previously. The aim of this paper is to show the evidence of using an evolutionary approach in early iron and steel production in Sri Lanka which is properly aline with the advance Physics principals and modern engineering technics.

III. Physics of the furnace

Tuyere and its Fluid Dynamics : Circular Shape: You have probably noticed that most fluids are transported in circular pipes. This is because pipes with a circular cross section can withstand large pressure differences between the inside and the outside without undergoing significant distortion. Noncircular pipes are usually used in applications such as the heating and cooling systems of buildings where the pressure difference is relatively small, the manufacturing and installation costs are lower, and the available space is limited for ductwork.

The maximum possible efficiency of the furnace greatly depends on the air flow through the tuyeres. In fluid mechanics the air flow has to be a laminar flow through the tuyere. Laminar flow is one of the most important parameter in fluid mechanics which can be determined by the number so called *Reynolds Number*. The laminar or turbulent flows can be simply explained from the following example. If you have been around smokers, you probably noticed that the cigarette smoke rises in a smooth plume for the first few centimeters and then starts fluctuating randomly in all directions as it continues its rise. Other plumes behave similarly. Likewise, a careful inspection of flow in a pipe reveals that the fluid flow is streamlined at low velocities but turns chaotic as the velocity is increased above a critical value. The flow regime in the first case is said to be laminar, characterized by smooth streamlines and highly ordered motion, and turbulent in the second case, where it is characterized by velocity fluctuations and highly disordered motion. The transition from laminar to turbulent flow does not occur suddenly; rather, it occurs over some region in which the flow fluctuates between laminar and turbulent flows before it becomes fully turbulent. Most flows encountered in practice are turbulent. Laminar flow is encountered when highly viscous fluids such as oils flow in small pipes or narrow passages.

Reynolds Number: The transition from laminar to turbulent flow depends on the geometry, surface roughness, flow velocity, surface temperature, and type of fluid, among other things. After exhaustive experiments in the 1880s, Osborne Reynolds discovered that the flow regime depends mainly on the ratio of inertial forces to viscous forces in the fluid. Therefore the Reynolds Number, *Re*, can be written as;

$$\mathrm{Re} = \frac{v_{av} D}{\nu}, \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where v_{av} is average fluid flow speed in m/s, D is characteristic length of the geometry (diameter for a circular pipe) and ν is kinematic viscosity of the fluid in m^2/s. Kinematic viscosity of air in different temperatures and 1 atm pressure shown in Table 1. Note that the *Re* is a dimensionless quantity. The Reynolds number at which the flow becomes turbulent is called the critical Reynolds number, Re_{cr}. The value of the critical Reynolds number is different for different geometries and flow conditions. For internal flow in a circular pipe, the generally accepted value of the critical Reynolds number is $Re_{cr} = 2300$. Therefore, under most practical conditions, the flow in a circular pipe is laminar for $Re < 2300$, turbulent for $Re > 4000$, and transitional in between.

Table 1: Kinematic viscosity, ν and density ρ of air in different temperatures at1 atm pressure [9].

$T\ (^0C)$	200	400	600	800	1000	1500	2000
$\nu \times 10^{-5} (m^2/s)$	3.46	6.23	9.25	13.26	17.43	29.2	42.7
$\rho \times 10^{-3}\ (kg/m^3)$	746	524	404	329	277	199	155

Optimum Pressure Drop: A quantity of interest in the analysis of air flow through the tuyere is the pressure drop Δp since it is directly related to the performance of the furnace. This pressure drop due to viscous effects of the fluid. All the real fluids including air create friction against the motion and will contribute to pressure drop. The pressure drop for a laminar flow can be expressed as

$$\Delta P = \frac{32\,\rho\,\nu\,l\,v_{av}}{D^2}, \qquad \ldots\ldots\ldots\ldots \quad (2)$$

where l length of the tuyere and ρ density of air.

Inclined Tuyere: Then the volume flow rate, dV/dt, for laminar flow through a horizontal pipe of diameter D and length l becomes,

$$\frac{dV}{dt} = \dot{V} = \frac{\pi}{128}\frac{\Delta P D^4}{\rho \nu l}. \qquad \ldots\ldots\ldots\ldots \quad (3)$$

The pressure drop Δp equals the pressure loss in the case of a horizontal tuyere, but this is not the case for inclined pipes or pipes with variable cross-sectional area. This can be demonstrated by writing the energy equation for steady, incompressible one-dimensional flow.

Relations for inclined pipes can be obtained in a similar manner from a force balance in the direction of flow. It can be shown that the volume flow rate relation for laminar flow through inclined tuyere is,

$$\dot{V} = \frac{\pi}{128}\frac{(\Delta P - \rho g l \sin\theta) D^4}{\rho \nu l}. \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

which are identical to the corresponding relations for horizontal pipes, except that Δp is replaced by (Δp-ρgl sinθ). Note that $\theta > 0$ and thus $\sin\theta > 0$ for uphill flow, and $\theta < 0$ and thus $\sin\theta < 0$ for downhill flow.
In inclined pipes, the combined effect of pressure difference and gravity drives the flow. Gravity helps downhill flow but opposes uphill flow. Therefore, much greater pressure

differences need to be applied to maintain a specified flow rate in uphill flow. Therefore, the downhill flow rate will be greater compared to uphill flow rate which can be seen from the following two equations.

For uphill, $$\dot{V}_{(\theta>0)} = \frac{\pi}{128}\frac{(\Delta P - \rho g l \sin\theta)D^4}{\rho \nu l} \quad \text{...............(5)}$$

and

For downhill, $$\dot{V}_{(\theta<0)} = \frac{\pi}{128}\frac{(\Delta P + \rho g l |\sin\theta|)D^4}{\rho \nu l}.$$

Table 2: Reynolds number, *Re* at 800 ^{0}C for air as a function of different average speeds, v_{va} and different tuyere diameters, *D*.

v_{av} $(m/s) \Rightarrow$ D $(m) \Downarrow$	4	6	8	10	12	14	16
0.020	603	905	1207	1508	1810	2112	2413
0.025	754	1131	1508	1885	2262	2640	3017
0.030	905	1358	1810	2262	2715	3167	3620
0.035	1056	1584	2112	2640	3167	3695	4223
0.040	1207	1810	2413	3017	3620	4223	4827
0.045	1358	2036	2715	3394	4072	4751	5430

III. Results and Discussion

Maximum combustion in wind-driven furnace requires a constant, steady supply of oxygen, here supplied from air, and the regulation of this air supply provides the primary method of control of the combustion process in a furnace. The simplest method for supplying this air is that of a natural draft of air within the furnace when heated expands, reducing its density, and buoyancy causes it to rise.

Natural draft can create high air flow rates under the correct circumstances. To maintain the maximum efficiency throughout the processing time, for 6 to 7 hours [1], the anural airflow through the tuyeres has to be in the transitional range. In other words, the Reynolds Number, should satisfies the condition: $2300 < Re < 4000$. Therefore, the most important part of the furnace is the tuyere. Proper dimensions of the tuyeres are largely contributed towards the performance of the furnace. The calculation of Reynolds numbers for air as a function of different average speeds, v_{va} and different tuyere diameters, *D* shown in Table 2. According to the field observations during the reconstruction in 1996, measured mean wind speed is 10-12 m/s. In addition to that archaeological evidence shows that the mean tuyere volume is in the range 210 cm^3 and l = 18-20 cm [1,7]. One can easily fiend the mean diameter of the tuyere based on this evidence, the value of *D* is 3.75 cm. Now one can compare the calculated values for *Re* given in Table 2 with mentioned values of *D* and v_{av}. Remarkably in this range *Re* satisfies the condition: $2300 < Re < 4000$. With their well developed traditional knowledge they were able to fulfil one of the most important parameter relevant to wind-driven furnace used in early iron and steel production.

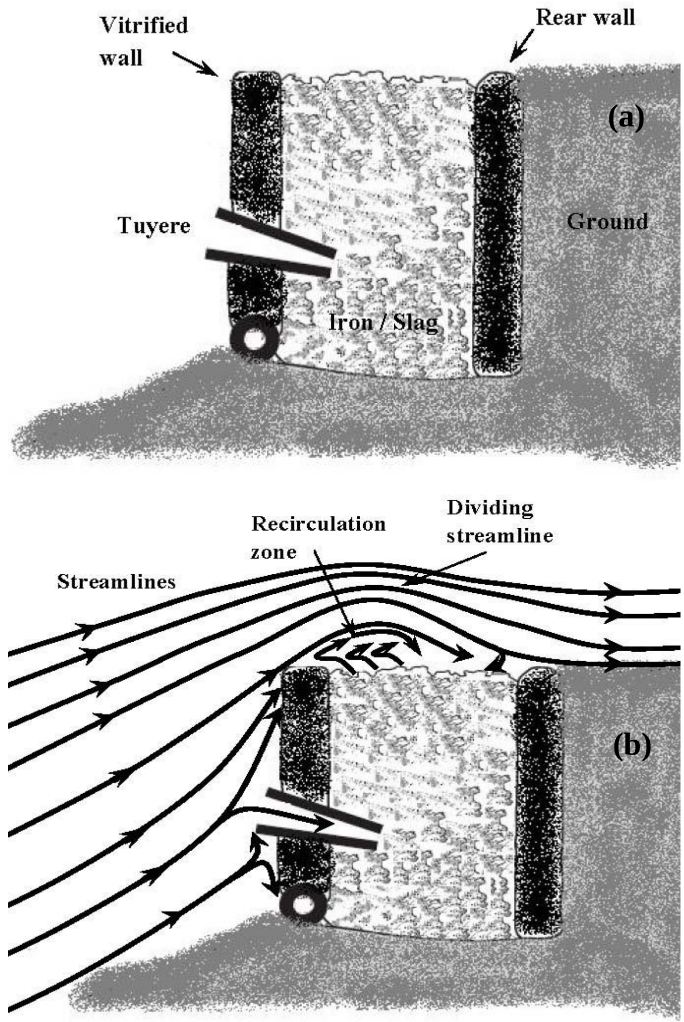

Fig: 2 (a) Cross-sectional view of the furnace. (b) Air flow around the furnace.

The mentioned resistance to flow will depend on the density of packing of the furnace. If the packing materials were spherical and of even size, in cubic close packing, one would expect them to pack together in a manner analogous to stacked balls, and thus we would find around 73% of the volume occupied by the materials. Practically the packing would likely be more random. However, the volume fraction would be similar. In these circumstances it is necessary to force airflow through the furnace. There are several ways of enhancing the air flow through the furnace. The furnaces discovered in Sri Lanka are situated in a region with a strong and dependable monsoon wind and are constructed at a consistent orientation to this prevailing wind [1,7]. This is probably to utilise this wind to draw air through the furnace. The furnace geometry can be seen in the Fig. 2(a).

The physical explanation of the furnace as follows, the wind blows up the side of the hill it meets the front of the furnace, and is diverted upwards. This leaves a region of stagnant air in front of the front wall. One of the fundamental theorem in fluid mechanics the Bernoull's theorem [10] states that the faster the air speed the lower the pressure, and thus in front of the furnace's front wall a high pressure region is formed (see Fig 2(b)). Due to the phenomenon known as boundary layer separation, wind reaches the top of the front wall continues in the same direction. Therefore, this produces a relatively low pressure area immediately above the furnace bed, and thus there is a pressure difference between the top (low pressure) and the front (high pressure). This creates a driving force to draw natural air into the furnace through the tuyeres.

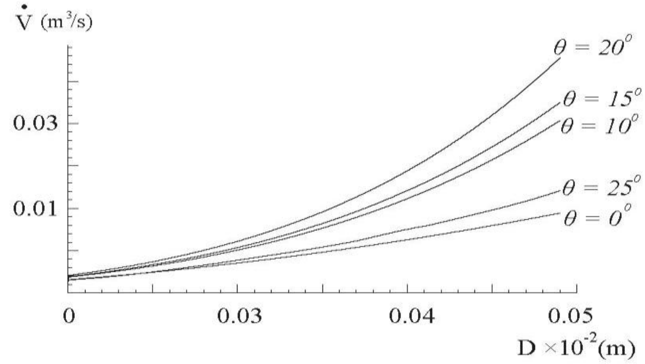

Fig: 3 Volume flow rate as a function of D for different θ.

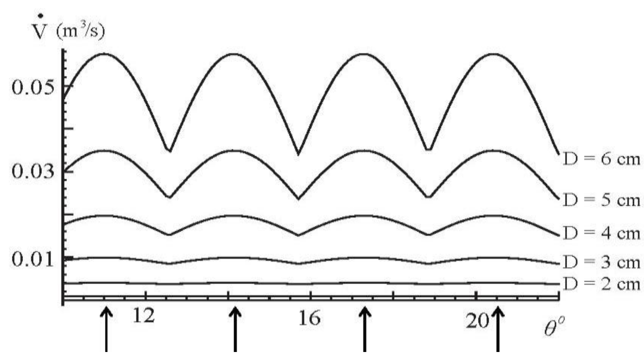

Fig: 4 Volume flow rate as a function of θ for different D. The θ values for maximum volume flow rate have been shown in the figure.

The calculated volume flow rate as a function of D for different θ shown in Fig. 3 and volume flow rate as a function of θ for Different D shown in Fig. 4. According to the data presented in Ref. 1 the mean angle of inclination of tuyeres is in the range 17^0-20^0. As shown in Fig. 3, calculated maximum flow rate for D = 4cm is maximum in the range 15^0-20^0. This result is in excellent agreement with the presented archaeological evidence in Ref. 1 and 7. Some particular values of θ will increase the volume flow rate significantly (see Fig. 4). According to the theoretical values shown in Fig. 4, the maximum performance can be achieved with $\theta \sim 11^0$, *14*, *17*, *20*^{0}. Presented data in Fig. 4 shows that the increasing diameter of the tuyere enhances the volume flow rate significantly. Sri Lankan engineers, with traditional knowledge and 2000 years experience of iron and steel production, were smart enough not to use large diameters. The modern engineering explanation is very simple. As we can see from Eq. 1, with increasing diameter also increase the Reynolds number, which enhance the turbulent conditions of the streamlines.

IV. Conclusion

We have developed a simple theoretical framework for proper investigation of the nature of technological development and the viability of applying an evolutionary approach to the early development of iron production in Sri Lanka. We hope that our work will be useful to establish a good connection between archaeological study and the scientific background of 2000 years old iron and steel production in Sri Lanka. Finally, these techniques could be enhanced with the proper scientific investigation like this work and could also be applied to similar pre-industrial technologies, such as other metal processing furnaces and pottery kilns.

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