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ΟΡΓΑΝΩΣΗ

ΕΤΑΙΡΕΙΑΣ ΔΙΕΡΕΥΝΗΣΗΣ ΤΗΣ ΑΡΧΑΙΟΕΛΛΗΝΙΚΗΣ ΚΑΙ ΒΥΖΑΝΤΙΝΗΣ ΤΕΧΝΟΛΟΓΙΑΣ

NOESIS
ΚΕΝΤΡΟ ΔΙΑΔΟΣΗΣ ΕΠΙΣΤΗΜΩΝ & ΜΟΥΣΕΙΟ ΤΕΧΝΟΛΟΓΙΑΣ

Το Διοικητικό Συμβούλιο της Εταιρείας Διερεύνησης της Αρχαιοελληνικής και Βυζαντινής Τεχνολογίας (ΕΔΑΒυΤ) ανέλαβε την ανάρτηση στην ιστοσελίδα της (www.edabyt.gr), σε ψηφιακή μορφή, των εργασιών του 3ου Διεθνούς Συνεδρίου Αρχαιοελληνικής και Βυζαντινής Τεχνολογίας (Αθήνα 19-21 Νοεμβρίου 2024).

Οι εργασίες είχαν γίνει αντικείμενο κρίσεων και σχολιασμού από την Επιστημονική Επιτροπή. Επι πλέον, έγιναν κι άλλες παρατηρήσεις και σχόλια κατά την συζήτηση που ακολούθησε μετά την προφορική τους παρουσίαση στο Συνέδριο.

Οι εργασίες αναρτώνται όπως κατατέθηκαν από τους συγγραφείς μετά την ολοκλήρωση του Συνεδρίου. Οι συγγραφείς φέρουν την ευθύνη του περιεχομένου της εργασίας τους, τόσο ως προς τις απόψεις τους όσο και ως προς την ακρίβεια και την ορθότητα των στοιχείων που παραθέτουν.

The Board of Directors of the Association for Research on Ancient Greek and Byzantine Technology (EDAByT) undertook the posting on its website (www.edabyt.gr) of the papers presented at the 3rd International Conference on Ancient Greek and Byzantine Technology (Athens, November 19-21, 2024).

The papers had been subject to reviews and comments by the Scientific Committee. Additionally, further observations and comments were made during the discussion that followed their oral presentation at the Conference.

The papers are posted as submitted by the authors after the conclusion of the Conference. The authors are responsible for the content of their work, both in terms of their views and the accuracy and correctness of the data they present.

THE ENDURING IMPACT OF CTESIBIUS' FORCE PUMP ON HYDRAULIC ENGINEERING AND TECHNOLOGICAL PROGRESS

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Abstract. Pioneering inventors such as Archimedes, Ctesibius, and Hero were instrumental in advancing ancient technologies, each contributing groundbreaking engineering solutions that laid the foundation for future developments. Their innovations not only addressed the immediate needs of their time but also influenced the course of technological progress for centuries. Among these contributions, Ctesibius's force pump stands out as a particularly significant innovation in the field of hydraulic engineering. Originally designed for essential tasks such as water supply, irrigation, and drainage, the principles underlying the force pump have endured over the centuries. These principles continue to influence modern technologies, particularly in municipal water systems, agricultural irrigation, and various industrial processes. This research delves into the broader concept of innovation as understood in ancient Greek thought, illustrating how the Greeks' deep appreciation for new ideas and inventions fuelled advancements across multiple domains, from engineering to philosophy. The force pump developed by Ctesibius has been thoroughly studied by scholars, often considered a perfected example of ancient hydraulic engineering. However, this study revisits Ctesibius's key innovations, including the introduction of one-way valves, a double-cylinder design, and a piston mechanism. These advancements significantly improved water flow and efficiency, making the force pump a more effective tool for a variety of applications. Furthermore, Ctesibius' use of metal components, rather than the traditional wood, enhanced the pump's durability and precision, setting new standards for hydraulic engineering that would resonate through the ages. By tracing the applications of Ctesibius' pump in ancient times, particularly in the mining sector, and examining its continued relevance in contemporary contexts, this research highlights the force pump as a quintessential example of enduring innovation. The pump's versatility and effectiveness demonstrate how ancient technologies can transcend their origins, remaining relevant and influential in modern engineering. Ultimately, this study reveals that the legacy of Ctesibius' force pump extends far beyond its immediate technical achievements. It offers valuable insights into the importance of fostering innovation as a catalyst for sustained growth and societal well-being. This research underscores the timeless relevance of ancient innovations in shaping the course of human history and advancing technological progress across millennia.

Keywords: Innovation, Ctesibius, Force pump, Hydraulic engineering, Ancient Greece.

1 Introduction

In the 5th century BC, the discovery of substantial silver deposits in the Lavrion region marked a pivotal moment for ancient Athenians, profoundly impacting their economy and societal development. This newfound wealth not only bolstered Athenian Democracy but also sparked a cultural mindset associating mining discoveries with progress and innovation across various fields.

As the Athenians reveled in their newfound prosperity, inventors like Archimedes, Ctesibius, and Hero emerged in subsequent centuries, each contributing pioneering engineering solutions that laid the groundwork for future technological advancements. Archimedes, known for his contributions to mathematics and physics, conceptualized devices such as the Archimedean screw, which revolutionized water transportation and irrigation systems. Ctesibius, an inventor and mathematician, developed the force pump among other innovations, while Hero, a physicist and engineer, introduced the aeolipile, considered one of the earliest steam-powered devices. These inventions were not just technical novelties of their time; they catalyzed profound societal changes and laid the foundation for subsequent technological revolutions.

The force pump, attributed to Ctesibius, exemplifies this transformative impact. Originally designed for various hydraulic applications, including pumping water and maintaining water pressure in ancient public baths , the force pump later found diverse applications in agriculture, mining, and early firefighting efforts.

This study seeks to explore the enduring influence of Ctesibius' force pump, tracing its evolution through different epochs and examining its multifaceted applications. Beyond its technical utility, the force pump's societal impact will be scrutinized, evaluating how its adoption influenced economic practices, urban development, and technological advancement.

2 The concept of innovation

The term *καινοτομώ* (Greek: innovation) has its roots in ancient Laurion, where the Athenians discovered significant silver deposits in the 5th century BCE. The wealth generated from these mining operations became highly valued by the Athenian Democracy. This event had a profound impact on their thinking, associating the concept of a new cut (*καινο-τομώ*), or the opening of a new mine, with the broader idea of innovation across various fields of human activity, all of which had the potential to drive progress.

The use of the term "innovation" in ancient Greek literature can be traced back to Aristophanes, who employed it in his plays Wasps and Ecclesiazusae. Additionally, Xenophon uses the term metaphorically in a positive sense in his work Ways and Means. Aristotle also uses the term in the 4th century BCE (Politics 1265a.10-12), where he describes Socratic arguments as innovative and probing. Similarly, Plato, in the 5th century BCE (Laws 792b.8-c.2), uses "innovation" to refer to the capacity for introducing inventions and societal reforms. This historical context illustrates how the Athenians valued not only the discovery of new mines for their wealth and power but also innovations—whether technical inventions or social reforms—as transformative forces in society.

During the 5th to 4th centuries BCE, ancient Greek city-states experienced a surge of innovations that led to significant advancements in technical, theoretical, and empirical sciences. These innovations, often driven by military competition or the need to improve living conditions (such as optimizing water use in silver processing), catalyzed a series of interconnected developments that fueled the overall growth of city-states. This period

demonstrated how innovations in one domain—be it technical, philosophical, or political—spurred progress across multiple facets of society.

Xenophon, in his works Anabasis and Cyropaedia, discusses the use of technology in warfare, describing siege engines and other war machines that provided strategic advantages in battle. While he often emphasizes traditional tactics, he acknowledges the role of technological innovation in enhancing military effectiveness.

Similarly, in History of the Peloponnesian War, Thucydides recounts various technological innovations used during the conflict, such as the Athenians' naval advancements. The construction of the Athenian long walls and their triremes exemplify how technological advances were integrated into military strategy to protect and expand the state's power.

Technological advancements were recognized for their practical benefits, particularly in warfare, engineering, and craftsmanship. However, there was also a recurring theme of ambivalence, with concerns that technological progress could disrupt social order, lead to ethical dilemmas, or destabilize traditional values.

While technological innovation was not always the primary focus of ancient Greek literature, it was an important aspect of their broader discussions on the balance between tradition and change. The works of Herodotus, Xenophon, Thucydides, Plato, Aristotle, and others reflect this nuanced perspective, showing both the potential of technological innovation to enhance society and the risks it posed when not carefully managed.

3 The Ctesibius' force pump

Vitruvius, in his book De Architectura[1], provides a comprehensive description of the force pump, an invention attributed to the Hellenistic Alexandrian engineer Ctesibius, who made this innovation in the middle of the third century B.C. While working on a system of pulleys for a moveable mirror, Ctesibius realized the potential of air pressure when compressed and decompressed, leading to the creation of the first force pump.

The force pump consisted of a metal cylinder, a piston, two one-way valves, and a spout. The metal construction enhanced durability and allowed for precise engineering, with the piston fitting tightly within the cylinder to prevent water leakage. The one-way valves, positioned at the inlet and outlet of the pump chamber, ensured water flowed in a single direction. During the upstroke, water was drawn into the pump, and during the downstroke, it was expelled. Ctesibius' pump often incorporated a double-cylinder design, allowing continuous water flow—while one cylinder drew in water, the other expelled it, improving efficiency and ensuring a steady stream of water.

The pump operated through a hand-moved wooden lever that created a swinging motion, raising one piston to draw water in while the other piston expelled water through a central pipe, securing a continuous flow. This system worked best with clean water due to its operating mechanism.

Ctesibius's force pump functioned on the principles of pneumatics (air pressure) and hydraulics (fluid pressure), generating significant pressure differences within the cylinder to move water to greater heights and over longer distances than previous devices. The use of one-way valves ensured that water flowed only in the intended direction, preventing backflow and maintaining consistent output. The use of metal components, such as bronze or iron, marked a significant technological advancement, providing the necessary strength and

[1] Morgan M.H. 1914. *Vitruvius, The ten books of Architecture*, Chapter VII, pp. 298-299. Harvard University Press London: Humphrey Milford Oxford University Press.

precision to maintain tight seals and withstand continuous operation, enhancing the pump's durability and effectiveness.

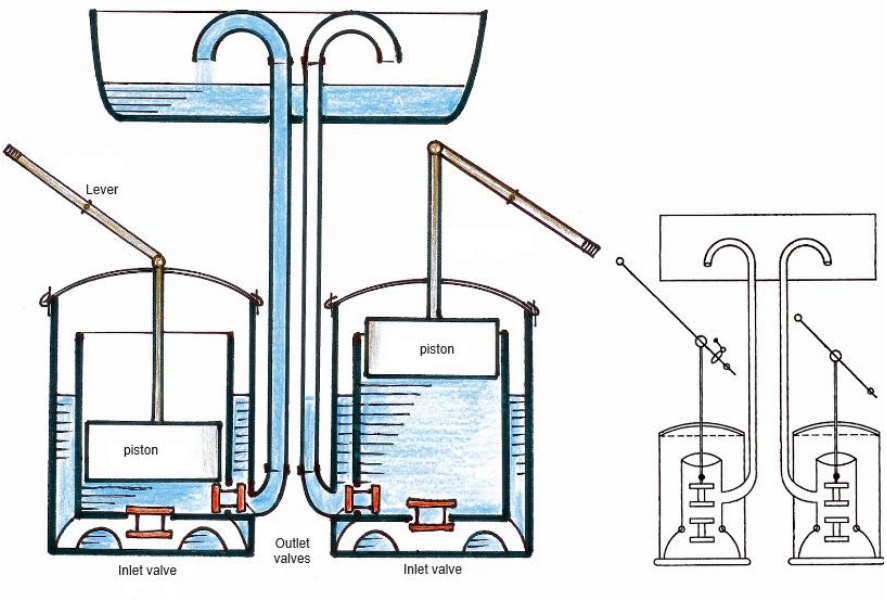

Figure 1. Left, Ctesibiu´s force pump (D. Kalligeropoulos). Right, Drawing of the Ctesibius´force pump as it is described at Phylo´s Pneumatics manuscript

In addition to his work on the force pump, Ctesibius advanced the theory behind cannons and made significant contributions to acoustics, including the invention of the first water organ. His understanding of the relationship between pressure and volume in a closed system, later formalized as Boyle's Law in the 17th century, laid the foundation for the study of hydraulics. His principles of pressure differentials, valve systems, and piston mechanisms became fundamental to fluid mechanics and were key in the development of more complex machines, such as steam engines.

The Romans adapted Ctesibius' force pump to include two cylinders operating alternately, yet still manageable by one person with a single handlebar. The pump was placed within a body of water, and when the bar raised one piston, drawing water into its cylinder, it lowered the opposite piston, forcing water out through a central outlet connected to a vertical pipe. A system of one-way valves ensured that water flowed correctly, and the alternating pistons created a constant jet of water.

The force pump represented a significant technological advancement over earlier water-lifting devices, such as the shadoof and the Archimedean screw. Its ability to generate higher pressures made it more versatile and effective for a variety of applications.

3.1 Innovation in Ctesibius' force pump

In the force pump, Ctesibius introduced a series of innovations that demonstrated his extensive knowledge and expertise in pneumatics and hydraulics.

The piston mechanism was a key innovation that transformed the efficiency of water lifting and movement. It consisted of a cylindrical chamber and a piston rod, operated manually. As the piston was pulled upward, it created a vacuum inside the cylinder, drawing water through an inlet valve. On the downward stroke, the piston would force the water out through an outlet valve. This mechanism allowed for controlled suction and discharge of water. By using a piston, Ctesibius was able to design a double-action pump, enabling water movement on both the up and down strokes, greatly enhancing efficiency. Unlike single-action pumps, which only

move water on one stroke, the double-action pump could displace water on both the upward and downward movements of the piston. On the upstroke, water was drawn into the cylinder through the inlet valve while water from the previous cycle was expelled through the outlet. On the downstroke, the inlet valve closed, and the piston forced water out through the outlet valve. This continuous flow of water during both strokes doubled the efficiency of water displacement, significantly enhancing the pump's operational capacity.

The valves were also crucial to its operation and innovation. These one-way valves were positioned at the inlet and outlet of the pump. During the piston's upward stroke, the inlet valve would open, allowing water to flow into the chamber, while the outlet valve remained closed to prevent backflow. On the downward stroke, the inlet valve closed, and the outlet valve opened, forcing water out. This design innovation ensured a smooth, continuous water flow, preventing leakage or loss of pressure. The incorporation of valves significantly improved pump efficiency and reliability for various applications.

The use of metal, particularly bronze that improved both durability and functionality. Bronze components were far more resistant to wear and corrosion than earlier materials like wood or clay. This allowed the pump to withstand continuous use and the stresses of water pressure without degrading quickly. The precision machining of metal parts also improved the fit and operation of the piston and valves, reducing leakage and friction. The strength and longevity of bronze made the pump more reliable for applications like firefighting and irrigation, marking a leap forward in hydraulic engineering durability.

These innovations not only made the force pump a more efficient device but also laid the groundwork for future advancements in hydraulic engineering. The principles introduced by Ctesibius' force pump continued to influence pump design for centuries.

3.2 Use and applications

The force pump had diverse and vital applications across several domains in ancient society. In firefighting, it was used to combat fires in urban settings by projecting water through hoses onto burning structures, significantly enhancing firefighting capabilities compared to traditional bucket brigades or other rudimentary methods. In agriculture, the force pump facilitated the efficient distribution of water from rivers, wells, or cisterns to fields, especially in areas where gravity alone was insufficient. This capability was crucial for sustaining agriculture in arid regions. For public water supply, the force pump was employed to deliver water to public baths, fountains, and other amenities in cities, thereby improving public health and hygiene. Its ability to pump water to elevated locations or over long distances made it particularly valuable in urban environments. In the mining sector, the force pump was used to dewater shafts and tunnels, enabling access to deeper mineral deposits. This application was especially significant in the Roman mines at Las Médulas in Spain and other mining sites across the Roman Empire.

Modern versions of the force pump play a crucial role in various contemporary applications. In municipal water systems, pumps based on the same piston and valve principles are essential for maintaining water pressure in pipelines, ensuring reliable water delivery to homes and businesses, including high-rise buildings. In agriculture, these pumps are used for efficient irrigation, particularly in regions where water must be lifted from wells or transported over long distances to large fields. The basic technology of the force pump also remains integral to modern firefighting equipment, where high-pressure pumps, often engine-powered, are vital for projecting water over long distances to combat fires, especially in large or hard-to-reach areas. In industrial settings, modern force pumps are employed in processes that

require the controlled movement of liquids, such as chemical processing, oil and gas production, and wastewater treatment, where handling large volumes of fluids is critical. Additionally, the principles of the force pump are applied in hydraulic systems used in machinery and vehicles, where controlled fluid movement powers actuators and motors, providing the necessary force for heavy lifting, braking, and other mechanical operations.

3.3 Case study: Mining sector

The removal of water from mines was one of the key issues that former miners had to deal with. Roman colonists brought new technology to the Iberian Peninsula that addressed this problem. Particularly in the Roman gold mines at Calañas and Las Médulas in Spain there are findings of drainage systems incorporating force pumps among other technologies.

Las Médulas was the largest open-pit gold mine in the Roman Empire, and its operations relied heavily on advanced hydraulic engineering. The force pump played a crucial role in dewatering the mine's deep shafts and tunnels, enabling the extraction of gold from previously inaccessible depths. The pump's efficiency in managing water allowed the Romans to exploit the rich deposits of gold in the region, contributing significantly to the empire's wealth.

Sotiel Coronada's mine (Calañas, Huelva) is known for the rich deposits of copper, zinc, lead and silver. During archaeological excavations several technological findings came into light showcasing the extensive use of them in the mining sector. In particular, Archimedes' Screw, Ctesibius' force pump and water wheels were used in order to drain the mining galleries and rich the mineral deposits for extraction.

Figure 2 Sotiel Coronada's pump, Calañas a Archaeological National Museum, (Madrid). b Drawing of a Ctesibius pump (Delgado-Domínguez & Pérez-Macías, 2013)

This pump (Fig. 2) was found in Huelva. Built in bronze and with a size of 0.95 m high and 0.41 m wide. It had a flexible tube with the form of a T placed at the end of the main tube. Due to their characteristics, it is believed that the main use of this pump was not to drain water but to pulverize it and cool the pyrite in the demolition system of the hard rock, where the action of the fre was complemented by the water[2].

[2] Suarez-Suarez, J., Puche-Riart, O., & Delgado-Dominguez, A. 2017. *Gonzalo y Tarin and the Physical, Geological and Mining Description of the Province of Huelva 1886–1888*. Boletin Geológico y Miniro, 128(1), 111–128.

This ancient technology set the stage for modern mining practices, where pumps continue to play a vital role in managing water in mines. Today, pumps similar in design to the force pump are used to keep modern mines dry, allowing for safe and efficient extraction of minerals.

3.4 Overall impact of the force pump

Ctesibius's work had a profound influence on both practical engineering and the theoretical study of pneumatics and hydraulics, fields that continued to develop over the centuries. Beyond its technological significance, the force pump had a substantial impact on ancient society, particularly in the Roman Empire, where it was widely adopted. In urban settings, the pump played a crucial role in supplying water to public baths, fountains, and homes, ensuring a consistent and reliable water supply. This was essential for maintaining public health and hygiene, as well as supporting the social and recreational activities that were central to Roman life. By facilitating water distribution in urban infrastructure projects, such as baths and fountains, the force pump contributed to the expansion and upkeep of public works, making cities more appealing to residents and visitors alike, which in turn stimulated economic activity through trade, tourism, and increased population density.

In agriculture, the force pump revolutionized irrigation, especially in arid regions where water had to be lifted from wells or transported over long distances. Its efficiency in providing water for crops significantly boosted agricultural productivity, leading to greater economic stability and growth in farming regions. The resulting surplus production facilitated trade and the development of local markets, further enhancing the economic vitality of these areas.

4 Conclusion

The principles introduced by Ctesibius' force pump have transcended time, continuing to influence modern technology. Today, the descendants of the force pump are integral to various sectors, including municipal water systems, agriculture, firefighting, and industrial processes. The continued relevance of these principles underscores the pump's role as a foundational innovation in hydraulic engineering, with its design influencing the development of more advanced pumps throughout history, from the Middle Ages to the Industrial Revolution and beyond.

This study has illuminated the broader concept of innovation as understood by the ancient Greeks, demonstrating how their appreciation for new ideas and inventions spurred progress across multiple domains. The force pump exemplifies how a single innovation can have far-reaching effects, not only solving immediate technical challenges but also shaping the trajectory of technological development and societal growth for centuries.

Ultimately, the legacy of Ctesibius' force pump extends beyond its technical achievements. It serves as a powerful reminder of the importance of fostering innovation as a catalyst for sustained growth and societal well-being. By continuing to study and draw inspiration from such ancient innovations, we can better understand the foundations of modern technology and the critical role that ingenuity plays in shaping the future.

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