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The Significance of Al-Jazari's Four-Bucket Water Lifting Machine in the History of Engineering and Science

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ABSTRACT: The developments in the field of engineering have an eclectic structure. During ancient times, the works carried out at the School of Mechanical Engineering in Alexandria were transmitted to the Islamic world through translations at the House of Wisdom (Bayt al-Hikmah). Following this process, engineering studies became the focus of research in the Islamic world, both from theoretical and practical perspectives. Prominent researchers in this context include the Banu Musa brothers (9th century), Al-Farabi (875-950), Al-Hazini (1100s), and Al-Jazari (13th century). The renowned Turkish philosopher Al-Farabi conducted research on air and vacuum, expressing his views in the treatise "Risale li-Ebi Nasr al-Farabi fi'l-Hala" (On Vacuum). Al-Hazini's book "Mizanu'l Hikme" (The Balance of Wisdom) sheds light on the concept of balance, with Hazini turning the water balance into an extraordinary equilibrium device and creating a balance called "Mizânü'l-Câmî" (The Collector).The Banu Musa brothers presented valuable machine and mechanical system designs in their work "Kitab al-Hiyal" (The Book of Ingenious Devices). Al-Jazari, born in 1153 in Cizre, served as the chief engineer of the Artuklu palace for 32 years. During this time, he designed many mechanical and automation-based systems. Upon examining the designs in Al-Jazari's book "Kitab-ül Cami Beyn-el-İl ve'l-Amel el-Nâfi fi Sınaât el Hiyel," it becomes apparent that he elevated the designs made before him to a completely different level. Some of today's engineering designs can trace their origins to the drawings found in this book.

In this study, the design features of Al-Jazari's 4-bucket water-lifting machine are examined, and its value in contemporary engineering is explored. Al-Jazari designed a mechanical timer to ensure the continuity of water flow in his design. This timer allowed each bucket to discharge water one after the other, maintaining a continuous flow of water. He achieved this through a shaft with quarter-toothed gears. This design can be considered the precursor to the eccentric and crankshafts found in modern internal combustion engines. The eccentric shaft controls the mechanical timing of valves in engines, while crankshafts ensure the continuous transmission of the force generated by four pistons in a four-stroke engine over a quarter of the cycle to the flywheel gear.

KEYWORDS: El-Jazari, mechanical timer, history of science, history of engineering.

I. INTRODUCTION

In the history of science and engineering, there are several pivotal moments and researchers who have contributed significantly to these turning points. When we follow written sources, we find that in the ancient period, individuals like Archimedes, Ctesibios, Heron, and Philo made important designs that laid the foundations for many engineering principles. Archimedes made significant contributions to hydraulic systems with his invention of the Archimedes screw. Ctesibios, on the other hand, contributed to the field with his work on water clocks and siphon systems [1]. During the Middle Ages, the role of being pioneers in science shifted to the Islamic world. With the establishment of the House of Wisdom (Bayt al-Hikmah), the legacy of engineering from the ancient periods was initially inherited, and then significant advancements were made in this field. In the context of mechanics and engineering, the designs created by the Banu Musa brothers played a crucial role in these advancements. Overall, these early pioneers in science and engineering, both in ancient times and during the Middle Ages, laid the groundwork for many important principles and innovations that continue to shape the field to this day. In the history of science, the Banu Musa brothers, namely Ahmed, Muhammed, and Hasan, are known for their significant contributions to various scientific fields. Among them, Ahmed Musa is particularly renowned for his work "Kitab al-Hiyal," which consists of designs that can be considered advanced versions of systems developed in the fields of mechanics, pneumatics, and hydraulics

at the Alexandria School of Mechanics. Various handwritten copies of this book can be found in libraries such as Topkapı in Istanbul, the Vatican, Berlin, Gotha, and Leiden. The book contains 100 designs and explanations, including drawings of fountains, siphon systems, lamps, fixed-level tanks, animal waterers, and various other mechanical devices. The work has also been translated into English by Donald R. Hill [2].

In the Islamic world, engineering designs made significant advancements in the 9th century, primarily thanks to the achievements of the Banu Musa brothers. However, it was in the 12th century that Al-Jazari, who lived in the 1100s, took these efforts to their zenith. Al-Jazari's designs are considered the starting point for modern cybernetic and automation systems. Born in 1153 in the Tor district of Cizre, Al-Jazari's full name was "Abu al-'Iz Ismail ibn al-Razzaz al-Jazari." His given name was Ismail, and his father's name was Razzaz. He carried the title "Abu al-'Iz," which means "Father of Honor and Dignity." He was named Al-Jazari due to his association with Cizre. Due to his exceptional designs for his time, Al-Jazari was called "Bediuzzaman," meaning "Wonder of the Age." This great inventor from Cizre is known as the foundational figure in computer science and technology, with contributions including robots, clocks, water machines, cipher locks, safes, thermoses, automatic children's toys, and 60 other inventions [3]. Al-Jazari passed away in 1233 in Cizre, and his tomb is located in the courtyard of the Nuh Prophet Mosque in Cizre. Al-Jazari spent 32 years as an engineer in the Artuqid palace, where he established numerous highly advanced technological devices that operated automatically according to the standards of his time. His most significant work in engineering was titled "Kitab-ül Cami Beyn-el-İl ve'l-Amel el-Nâfi fi Sınaât el Hiyel" (The Book of Knowledge of Ingenious Mechanical Devices). Al-Jazari's life's work, including the machines he designed and their operating principles, has been preserved to this day through this book.

What makes Al-Jazari significant in his era is the fact that his developed automatic systems and agricultural devices are still usable in today's technology. In this context, a publication examines an agricultural irrigation machine designed by Al-Jazari. Al-Jazari had numerous machine designs, and the reasons for selecting this particular machine within the publication lie in the fact that the mechanical systems used in it not only reflect the general characteristics of Al-Jazari's work but also possess engineering technologies that can be considered significant milestones in the history of science and technology today.

II. AL-JAZARI'S FOUR-BUCKET WATER LIFTING MACHINE

El-Jazari's designs, when examined, reveal that he created mechanical systems to meet the needs of his time and for entertainment purposes. These systems were built on mechanisms that could change the direction and rotation of force and motion, as well as transmission units. It's observed that these systems were powered by hydraulic energy and living (animal) energy sources [4]. Living in a feudal agricultural society, El-Jazari naturally focused on designs to address agricultural needs. A significant portion of his designs was dedicated to agricultural irrigation and time measurement systems. Anatolian lands, in particular, had significant potential in terms of water resources. As a result, dry farming practices were common in many parts of Anatolia. Dry farming practices reduced the variety of crops that could be grown and resulted in lower crop yields. Therefore, the management of water was crucial in the civilizations of Anatolia and Mesopotamia, where large feudal agricultural empires were established. During those times, civilizations that could transport agricultural irrigation water to agricultural lands and manage the seasonal changes in river flow rates for agricultural purposes became the dominant agricultural societies. Being an agricultural power for the states and empires of that era also paved the way for economic and military strength in their regions. Empires that could fill their granaries with agricultural products often grew in power, especially during times of famine, by subjugating smaller neighboring states and gaining an advantage over other empires. For these reasons, scientific endeavors during El-Jazari's time were focused on strengthening agricultural production and developing military technologies. In Kulcu's [5] study, an attempt was made to highlight the engineering significance of Al-Jazari's single-bucket water lifting machine. The important engineering aspects of the machine shown in Figure 1 were identified as the technological resemblances to contemporary mechanical technology, including differentials, semi-circular gear units, bucket elevators, and gearboxes, used in the machine's systems. The systems developed by Al-Jazari were certainly not identical in terms of materials and design to the mechanical systems used today. However, when evaluated in terms of their working principles and engineering principles, they are considered the ancestors of the systems used today. Furthermore, the fact that the designed systems were transformed into functioning machines, not just theoretical designs, demonstrates Al-Jazari's engineering genius.

After creating a design, Al-Jazari continued his efforts to improve that design. When his design book is examined, it reveals successive and enhanced versions of the same design. In this context, Al-Jazari constantly increased his contributions to the field of engineering through his improvements on the same design.

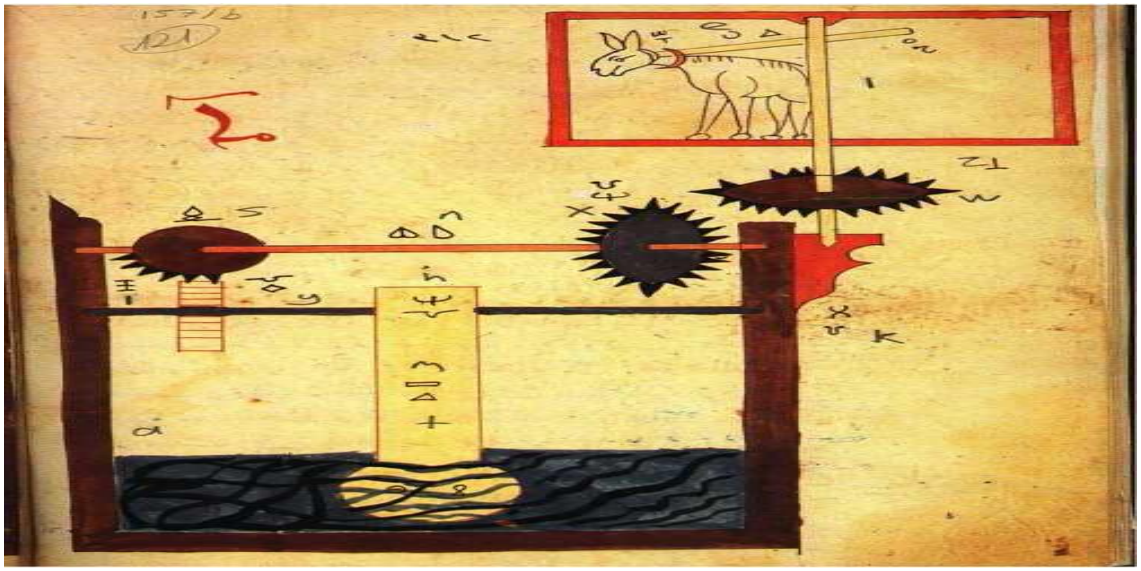

Figure 1. Al-Jazari's single-bucket water lifting machine [6]

In this study, an examination of Al-Jazari's four-bucket water lifting machine, which he developed by enhancing a single-bucket water lifting machine, was carried out (Figure 2). In his single-bucket water lifting machine, Al-Jazari aimed to eliminate the intermittent flow in the water flow due to the ¾ of the time or power transmission being idle, except for the ¼ time of water lifting by a single bucket. In this context, he designed the four-bucket machine shown in Figure 2. The machine is powered by an animal. The motion obtained from the animal causes the rotation of a shaft. The vertical rotating shaft, through a gear transmission system, increases the power and changes the direction of motion to rotate a horizontal shaft. There are four gear systems on the horizontal shaft. These gears have ¼ sections designed as teeth, and the remaining parts are flat. The flat and toothed sections on the gears are not symmetric but follow each other in an alternating pattern. The gears on the horizontal shaft move the buckets in the water. As the shaft rotates, the gears also rotate, and when the toothed parts of the gears come into contact with the gear that moves the bucket, the bucket lifts some water from the water source upwards. Because the ¼ teeth of the gears on the horizontal shaft are designed to follow each other, the buckets are moved sequentially. When the buckets in Figure 2 are numbered from left to right as 1, 2, 3, 4; with the rotation of the shaft, first 1, then 4, followed by 3 and 2 numbered buckets will operate. When one rotation is completed, motion will reach bucket 1 again. This design results in a machine where water flow occurs as long as motion is sent to the shaft. In this context, a new and superior design has been put forward by developing the design in Figure 1.

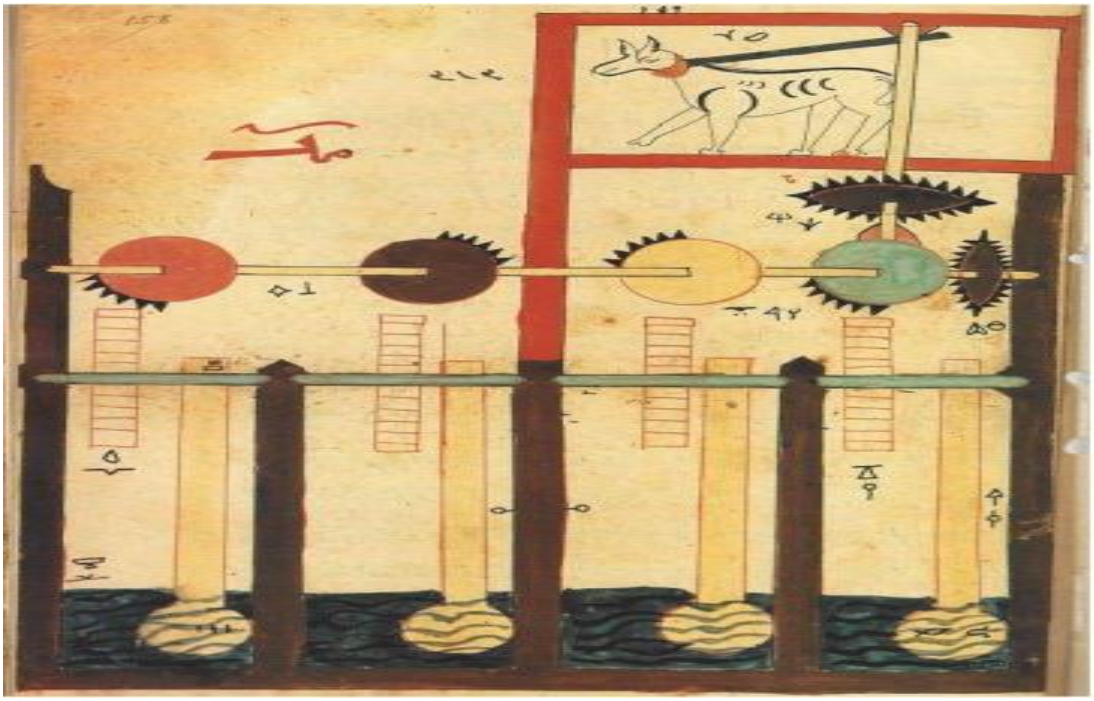

Figure 2. Al-Jazari's four-bucket water lifting machine

II. THE ENGINEERING SIGNIFICANCE OF AL-JAZARI'S FOUR-BUCKET WATER LIFTING MACHINE

In his first design, Al-Jazari made significant engineering contributions. The engineering significance of this system has been presented in detail by Kulcu [5]. In the second design, the system he developed to eliminate the intermittency in water flow also contains very important mechanical designs, just like in his previous design. What makes the four-bucket design important from the perspective of modern engineering is its mechanical timer quality. Timing mechanisms play a crucial role in the operation of machines. In this machine, the mechanical timing system that allows the water lifting buckets to operate sequentially ensures that the system operates automatically in a specific order. Disrupting the order of these buckets would disrupt the continuity of water flow, and if multiple buckets were to work simultaneously, it would increase the power requirement and cause the system to stop. In his design, Al-Jazari used a mechanical timer based on gear principles.

Today, mechanical timing is applied in many fields. However, the most common machines where mechanical timing is used are internal combustion engines. A significant portion of these engines consists of four-stroke engines [7]. Four-stroke engines, like Al-Jazari's design, are based on the principle of sequential operation of four separate cylinders. In these engines, each cylinder produces power in a ¼ time cycle. This power is sequentially applied to the crankshaft, ensuring that the motion is continuous rather than intermittent.

The motion sequentially taken from the engine pistons is received by the crankshaft and transmitted to the power transmission components of the vehicle by being delivered to the flywheel gear (Figure 3). Of course, engine types and designs may vary. However, the mechanical sequencing feature used in this design bears a fundamental resemblance to Al-Jazari's mechanical sequencing principle.

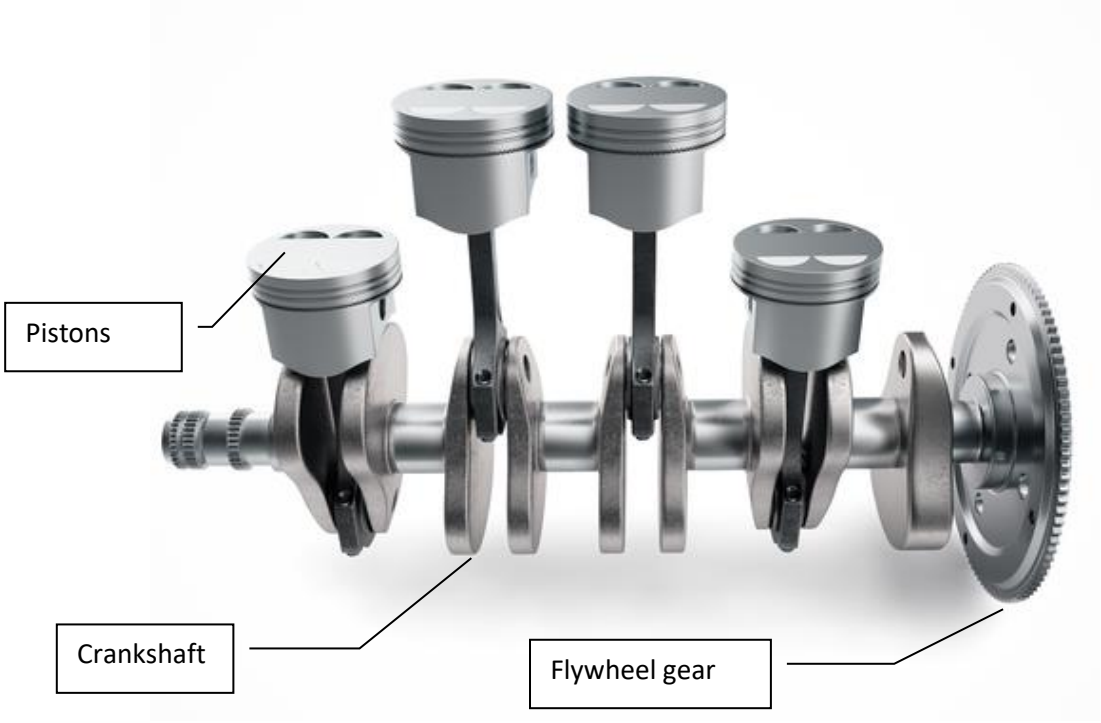

Figure 3. Piston, Crankshaft, and Flywheel Gear of a Four-Cylinder Engine [8]

In internal combustion engines, while the motion taken from the flywheel is transmitted to the power transmission components, a portion of the motion is also transmitted to the eccentric shaft through a timing belt. The eccentric shaft is responsible for providing motion to the valves that control the intake of air and the exhaust of gases into the engine cylinders. However, in a four-stroke engine, the opening and closing of these valves must be carried out in a specific sequence. This sequencing is achieved by eccentric designs on the eccentric shaft (Figure 4).

Figure 4. Eccentric shaft [9]

Eccentric designs on the eccentric shaft, once the rotational motion begins, push the valves located inside the engine block's cover forward. If the pushed valve is the exhaust valve, it allows the expulsion of post-combustion gases, and if it's the intake valve, it lets in the necessary fuel for combustion into the cylinder. There are two valves for each cylinder. Timing is of critical importance in this system. The timing of the valves in the engine is provided by the eccentric shaft design, which acts as a mechanical timer (Figure 5). In this context, the crankshaft and the eccentric shaft are responsible for the timing of the engine's operation.

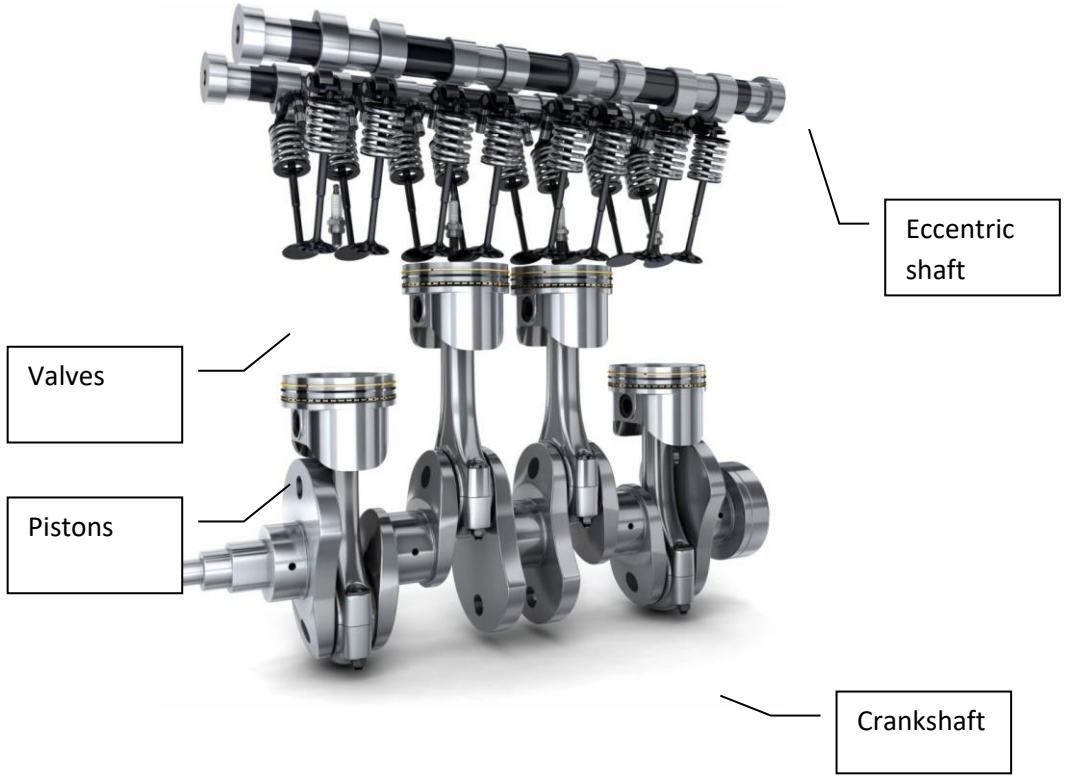

Figure 5. Crankshaft, pistons, valves, and eccentric shaft [10]

III. CONCLUSION

One of the remarkable achievements within the scope of this publication is the examination of a four-bucket water lifting machine. Al-Jazari's design innovations in this machine demonstrate significant engineering accomplishments. However, what sets his design apart from previous ones is the utilization of a mechanical timing mechanism to overcome the discontinuity in water flow. This mechanical timing mechanism, when evaluated in conjunction with transmission and power transmission principles, can be considered the precursor to the crank and eccentric shafts used in modern internal combustion engines. Mechanical timing devices are not exclusive to internal combustion engines but are also applied in various control systems, timekeeping instruments, and mechanical designs. Nevertheless, the structural resemblance between Al-Jazari's design and components used in internal combustion systems is noteworthy.

In conclusion, when evaluating Al-Jazari's design in the context of engineering history, the following features stand out:

- The use of a transmission system to increase power.
- A gear system that changes the direction of motion.
- The incorporation of a mechanical sequencing feature in the form of a ¼ gear wheel system.
- A bucket water lifting mechanism that ensures continuous water flow.

These features demonstrate Al-Jazari's significant contributions to engineering and mechanics, particularly in the field of agricultural machinery. His innovations laid the groundwork for important engineering principles and technologies that continue to be relevant in various applications today.

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