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Innovation of Mechanical Machinery in Medieval Centuries, Part II: Water Pumps, Clocks and Robotics

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***Abstract*— The fascinating mechanical inventions aiming at the welfare of the human kind started from ancient Egyptians and continued development through different eras. In the medieval centuries, the Islamic civilization paid wonderful attention to mechanical engineering. Al-Jazari invented 50 mechanical devices including water and candle clocks, positive displacement pumps and robotics. Taqi Al-Din invented a 6-cylinder positive displacement pump and the mechanical geared clock. Those great inventers used clean-energy prime movers in the form of windmills, overshot water wheels and undershot water wheels (turbines). This paper focuses only on water pumps, clocks and robotics.**

***Index Terms*— Muslim civilization, Mechanical machinery inventions, Water pumps, Clocks, Robotics.**

I. INTRODUCTION

Mechanical machinery in the medieval centuries used clean sources of energy to generate motion and mechanical power. The genius Arabic mechanical engineers invented positive displacement pumps, mechanical clocks and robotics with various applications. The role of Arabic/Muslim engineers in this field is clarified by a large number of researchers, scientists and mechanical engineers around the whole world.

Hill (1974) translated an annotated Al-Jazari manuscript on ingenious mechanical devices. As a mechanical engineers he reproduced some of the manuscript drawings and provided modern explanations for their operation. He also handled the Islamic technology up to Al-Jazari including the works of Banu Musa, Al-Khuwarizmi and Ridwan [1]. Hill (1977) a manuscript dated 1266 AC belonging to Ibn Muadh Al-Jayyani (died 1079 AC). He pointed out that Al-Jayyani treatise consists of 31 models in which models numbers 1-5 are very large toys similar to automatic clocks but without precise timing. While models numbers 6-20 and 27-30 are water clocks recording the hours by a moving automata. Models numbers 25 and 26 are raising water machines. Finally, models numbers 21-24 are war machines and 31 is a universal sundial [2]. Al- Hassan (1977) presented the manuscript of Al-Jazari after redrawing some of Al-Jazari machines with English letters concentrating on Al-Jazari machines for raising water. He provided an English-Arabic Glossary for the terms used in Al-Jazari manuscript [3]. Coomamswamy (1994) pointed out that the Museum of Fine Arts of Boston possesses six leaves of the Arabic manuscript on Automata. He inferred that Al-Jazari was first and foremost a craftsman and secondarily an author. His writing was intelligible and his diagrams were clear explaining his practical experience [4]. Hill (1998) claimed that until modern times there was no other document from any cultural area that provides a comparable wealth of instructions for the design, manufacture and assembly of machines like that of Al-Jazari who was a creative added several mechanical and hydraulic devices. The impact of Al-Jazari inventions (as he said) was seen in the later design of steam engines and internal combustion engines [5].

Mansour (2002) pointed out that there were recorded contributions to the area of automatic control. He investigated the work of Banu Musa, Al-Muradi, Ridwan Al-Saati and Al-Jazari [6]. Shakerin (2004) provided a review of innovative fountains developed through history including Al-Jazari's fountains [7]. Hassaan (2004) introduced Banu Musa as the founders of feedback automatic control in the 9th century AC and reviewed their scientific activities with emphasis on their book "Kitab al-Hiyal" (Ingenious Mechanical Devices". He analyzed two of their level control systems [8]. Sindi (2005) clarified that some Arab clocks had their time pieces moved by water, burning candles and mercury. He pointed out the known historical event of the gift of Abbasid Caliph Haroon Al-Rashid (died 809 AC) to the French King Charlemagne which was a water clock, and how the French king was totally impressed by it [9]. Al-Hassan (2007) described the operation of the elephant clock of Al-Jazari and the characteristics of a physical model built and located in Ibn Battota Mall, Dubai. The model weighs 7.5 ton and has 7 m height. He also described some of Banu Musa inventions such as the mechanical jars [10]. Nadarajan (2007) declared mechanical devices was the most comprehensive and methodical compilation of the most current knowledge about automated devices and mechanics [11]. Al-Hasssan (2008) analyzed the geometric and physical principles lying behind the mechanical devices of Banu Musa with the help of basic line drawings and 3D computer generated representation. He presented the basic shapes of Banu Musa fountain outputs which are: lily, shield and spear styles. He referred to the use of Banu Musa of wind/water tutbine to alternate water shapes [12]. Uzun and Vatansever (2008) stated that Al-Jazari invented the crankshaft and some of the first mechanical clocks driven by water and weight. They said that his use of crankshaft came before the western engineers Francesco Martini and Leonardo Davinci [13]. Abdallah (2009) focused the light on the fact that Muslim scholars, inventors and mechanical engineers used dynamics of water and its power to design and control mechanical devices. He presented the elephant clock of Al-Jazari and its available physical model. He stated that this clock is classified as fine technology as it is

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used for amusement or for astronomical observation and computation [14].

Romshare and Zeghloul (2010) pointed out that two of Al-Jazari machines are most remarkable: his elephant clock and one of his water pumps. The elephant clock was the most sophisticated clock at that time, and the water pump used a crank-slider-like system which was the first known machine to use a crank [15]. Ambrosett (2010) pointed out that in the Arabic world from Baghdad to al-Andalos, mechanical culture and practice underwent an extraordinary development. She mentioned the work of Banu Musa, Al-Jazari and Al-Muradi as witnesses of the extraordinary level of development of the mechanical devices [16]. Masood (2010) declared that Banu Musa designed industrial and scientific machines. They described devices in their book about ingenious devices such that each one had a master piece of ingenuity [17]. Shuriye and Faris (2011) pointed out that in the Islamic history of knowledge, engineering ranked high and their engineeris have made immense contributions to this field. Early scholars including Al-Battani, Al-Bairuni, Al-Razi, Jabin Ibn Hayyan and Al-Zarqali have mastered engineering sciences for the service of mankind [18]. Bruton (2011) presented Al-Jazari elephant clock as in one of his manuscript copies and a physical model built for the clock. He also presented a physical model for Al-Jazari castle clock, a copy and physical model of his cup clock and one of his positive displacement pumps [19]. Ness et. al. (2011) described the adaptation of available techniques to deal with one of the practical problems experienced with music robots. They pointed out the mechanical birds playing piano as in the early 19th century. This means that they did not read the translation of Al-Jazari treatise by Donald Hill in 1974 [20]. Dergisi (2012) presented and described the colored design of Al-Jazari for the elephant clock and the two-cylinder positive displacement pump [21]. Still (2013) braised the work of Banu Musa , Al-Jazari as designers of programmable music players, humanoid automata that depicted many machines such as one that measures blood letting was established with a pair of automatic scribes [22]. Mangun (2014) acknowledged the Islamic civilization emerged around 750 and prolonged until around 1500 where theoretical studies, discoveries, innovation and inventions had been encouraged to improve the lives of people during the Islamic Golven Age [23]. Ul-Haque (2014) pointed out that in the Islamic society, several individuals and groups of scientists devoted their life towards mechanical engineering and automation. He talked about the three brothers (Banu Musa) and Al-Jazari and how they contributed to the development of mechanical engineering [24].

II. WATER PUMPS

The ancient Egyptian invented the shadouf as a manually driven positive displacement pump for irrigation purposes. In medieval centuries, Al-Jazari introduced the technology of the design of positive displacement pumps for increased flow rate.

He presented in his great book about ingenious devices five designs of positive displacements pumps. Only two of them will be presented here. Figs.1 and 2 depicts two positive displacement pumps of Al-Jazari.

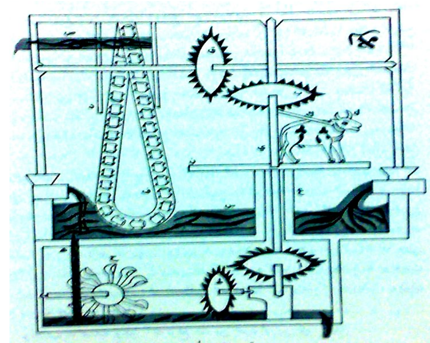

Fig.1 Buckets automatic pump of Al-Jazari [27].

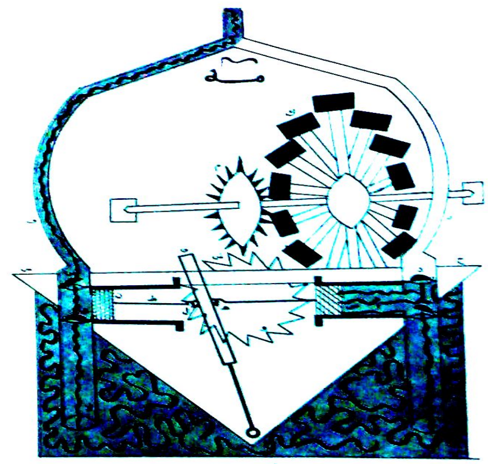

Fig.2 Two cylinders automatic pump of Al-Jazari [27].

In the design of FIg.1, an overshot water wheel is used to drive a compound gear train of bevel gears type to transfer power from the horizontal shaft in the bottom to the other horizontal shaft in the top. The top shaft drives a drum driving a rope-buckets assembly to raise the water from the pool above the water wheel chamber to the outlet channel of the pump just above the output shaft of the gear train. The pump is completely automatic in its drive. The shown driving animal is a dummy one and it has no role in driving the pump.

In the design of Fig.2, Al-Jazari put this innovative design which was the first step towards inventing the mechanism of the internal combustion engines. An undershot water wheel is used to drive a simple gear train which drives directly a crank-oscillating lever-slider mechanism. This mechanism transforms the rotational motion of the crank (the second gear of the simple gear train) to a translation motion of the pump two pistons. The vertical suction pipes are provided by two non return valves facing each cylinder end in opposite directions. During suction, the bottom valve opens and the delivery valve closes, while during delivery, the suction valve closes while the delivery valve opens. By this idea it is a two cylinders positive displacement pump driven automatically using a water wheel.

Now, we come to the pumps of Taqi Al-Din (died 1585 AC). He described four positive displacement pumps in his book "lighting ways in spiritual machines" (in Arabic) [28]. Only two of them will be described in this work. Figs.3 and 4 show two pumps of Taqi Al-Din.

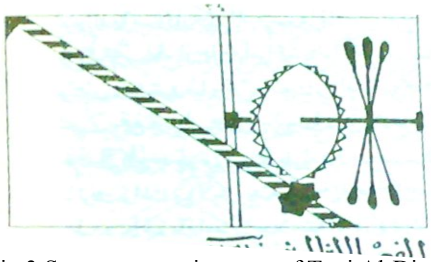

Fig.3 Screw automatic pump of Taqi Al-Din [28].

Fig.3 shows the screw pump of Taqi Al-Din. It is an automatic pump driven by an undershot water wheel. The wheel drives simple gear train with its pinion connected to the screw of the pump to suck the water and delivers it upward. This design is still in use till now in many applications due to its high efficiency [29].

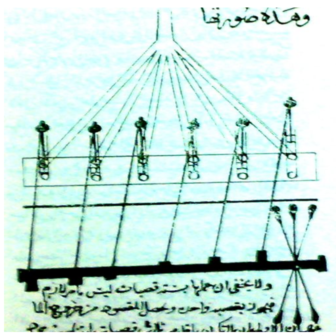

Fig.4 6-cylinders automatic pump of Taqi Al-din [28].

The 6-cylinders positive displacement pump of Taqi Al-Din is shown in Fig.4. It uses a water wheel to drive a camshaft. The camshaft supports 6 cams, each cam drives a connecting rod connected to the piston rod of on of the pump cylinders. This design used deadweights to return the pistons back during the downward stroke.

III. CLOCKS

Ibn Ismail Al-Jazari invented various types of clocks with various driving techniques. Only two of his designs will be handled In this work. Figs.18 and 19 show two of his designs [27].

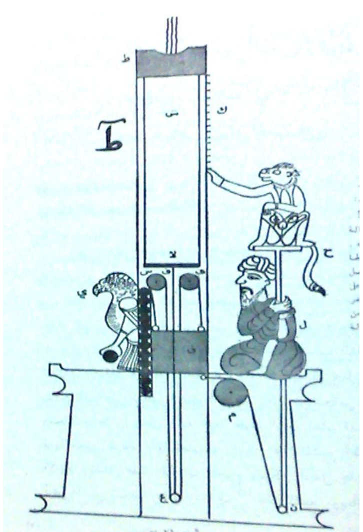

Fig.5 Candle clock of Al-Jazari [27].

Fig.5 shows a candle clock invented by Al-Jazari. It is a night clock since a candle ض spreads light in the night and in the same time drives the clock mechanism. It depends on the principle of varying weight of the candle as it burns. The clock mechanism consists of dead weight, 3 pulleys, (candle, base and base-rod), 2 rods at ع and ن , hours graduation scale at ك , bird at ي , (monkey at ح , base plate and base rod), man holding the monkey rod, cords and 12 balls.

This clock works for 12 hours of the night as follows: As the candle is set on its base the dead weight settles at a position corresponding to the beginning of the hours scale with the monkey pointing by its finger to it. As the candle burns, its mass decreases causing the dead weight to move down and through the cords raises the candle base upward and moves the donkey upward pointing to the time on the time scale. When a complete hour elapses, the hole in the bird faces one of the metallic balls in the balls holder allowing it to pass through the bird mouth to the clock frame making high sound announcing passing one hour.

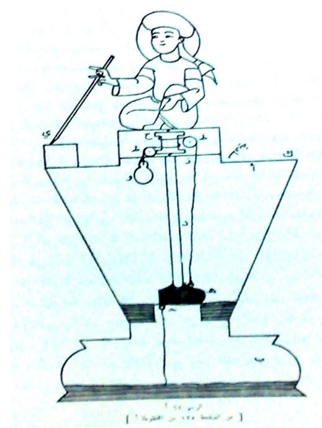

Fig.6 Cup clock of Al-Jazari [27].

Fig.6 shows a cup clock working with the principle of water flow through orifices. It consists of a cup holding inside a vertical axle with a float at its bottom end free to slide on it vertically and carries a pulley at its end free to rotate on it, orifice in its bottom discharging to a reservoir taking the shape of the cup base. The pulley is driven by a cord connected to the float and to a dead weight at its other end. The orifice is accurately designed to discharge at a specific flow rate to cover the time period of the clock. The pulley drives a setting robot holding a pencil pointing to the clock scale to read the time.

The clock works as follows: The cup is filled with water. The float is in its highest position with the clock pointer at the zero time on the scale. The water level and the float drop gradually at a rate controlled by the orifice dimensions. As the float drops, the cord around the pulley rotates it with the man holding the clock pointer. The volume of the bottom reservoir will take all the water flowing to it. At the end, this water can be fed again to the main cup. That is no water losses at all.

Taqi Al-Din introduced the third generation of clocks. That is the geared clocks. Fig.7 shows a geared clock from his manuscript about "spiritual machines" [28]. This design requires deep knowledge about mathematics, astronomy, machine design and production engineering. The clock provides the time, day and month in Arabic and Sun calendaring.

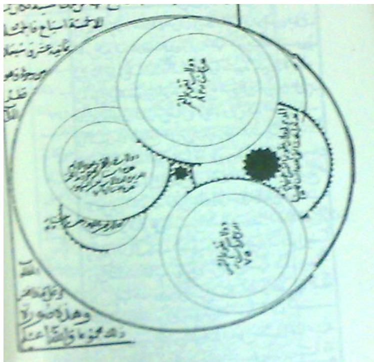

Fig.7 Geared clock of Taqi Al-Din [28].

IV. ROBOTICS

Ibn Ismail Al-Jazari invented robotics in the 12th century AC. He presented in his book about ingenious devices different types of robotics: single standing robots, single settling robots and multiple robots accompanying water clocks and automatic musical bands. He used hydraulic power and dead weights to drive the robots and his unique cuff to control the time and drive some of the robot elements. Figs. 8 through 11 show some of his robotic inventions.

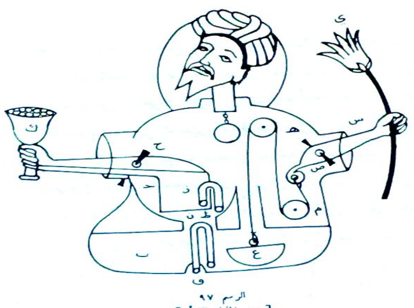

Fig.8 Setting robot of Al-Jazari [27].

In the setting robot shown in Fig.8, both hands of the robot move and his head is designed to oscillate. The working medium is a liquid, any liquid. The purpose of the robot is to collect waste liquids and get red of them in an automatic way through a drainage system. Both hands are pivoted in the middle (first class lever), the left hand holds a tree branch, the right hand holds a cup to collect the waste liquid in it, the head is pivoted at the neck with a dead weight to control its oscillation frequency. The right hand of the robot is ended with a small tank to collect the waste liquid until the liquid reaches the top of the siphon in the tank to discharge the liquid in the main tank ب and then the hand rotates counterclockwise to an equilibrium position. Now, there is a float ع in the main tank to sense the level of the liquid in the tank and drive the left hand of the robot using 2 pulleys with axles fixed to the robot body an a cord connecting the float and left hand. The position of the flower ي is an indication of the liquid level in the main tank ب . As the level of the liquid in the main tank increases, the float raises up, the robot left hand drops down until the liquid level reaches the top of the second robot siphon in the main tank. Then the siphon discharges all the main tank liquid to the drainage system. Then float ع moves down and the left hand moves up hitting the robot head which will oscillate as a compound pendulum.

Fig.9 shows a standing robot of Al-Jazari. The objective of this robot is to pour juice in a cup after a specific period of time. It depends of the principles of fluid mechanics and lever dynamics. The head of the robot contains a juice tank from which the juice flows through an orifice of predetermined diameter to control the juice flow rate to his hydraulic timer (the cuff at ع). When the cuff is filled with the specific volume required to fill the cup, cuff unbalance exists and the cuff turns clockwise pouring the juice to tank ص . Now, this juice flows through a channel ط to the fish. This amount in the fish is sufficient to move the left hand of the robot about its pivot counter-clockwise to drop the fish down towards the cup where the juice flows from its mouth to the cup. The right hand of the robot is pivoted in the middle as a first class lever with the cup at one side and a dead weight in the other side to make the hand rotates clockwise when the cup is removed from the hand to be ready to start a new cycle of filling the cup after certain period.

Fig.9 Standing robot of Al-Jazari [27].

Fig.10 shows a mobile robot of Al-Jazari. It works by principles similar to those of the design in Fig.9. However, the juice tank is separate on the top of a cabinet and bigger than that in Fig.9. The orifice lies in the bottom of the tank and pours the liquid into the cuff. Upon cuff unbalance, the liquid is poured in a small tank from which it flows through a wider orifice to the cup. The right hand of the robot is latched to the back of the cupboard to keep the robot in the backward position. The amount of liquid in the cup is sufficient to apply a force on the right hand pivoted in its middle to unfasten the robot with the cabinet. Because the robot can move by set of rollers, and the floor of the cabinet is inclined as shown in Fig.23, the robot moves forward, opens the 2 doors of the cabinet with his left hand holding a handkerchief while the right hand is holding the cup filled with juice or any other liquid. The user can push the robot manually backward to latch with the cabinet and start a new cycle.

Fig.10 Mobile robot of Al-Jazari [27].

Fig.11 shows a multi-robotics boat-music band operated automatically using water power. The boat caries a water reservoir feeding water through an orifice to Al-Jazari cuff which is a hydraulic timer. After a specific time the cuff is turned anticlockwise , looses its stability and pours its contents a another small tank to discharge its contents through another nozzle towards the overshot water wheel. The water wheel rotates and drives the directly coupled camshaft carrying four offset cams. Each cam drives a musician through a follower. The music band provides also whisking through a sealed chamber at ك . When this chamber is filled it discharges automating through a siphon to the bottom tank in the boat.

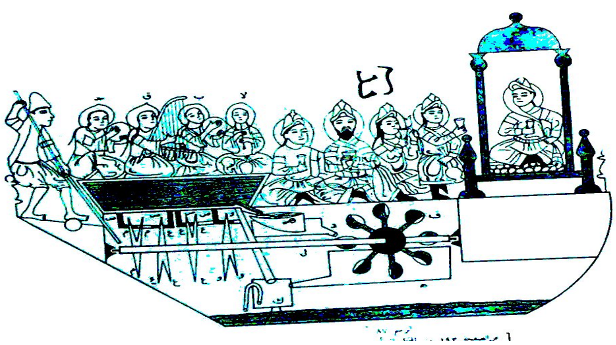

Fig.11 Multiple musician robots of Al-Jazari [27].

CONCLUSION

- The Muslim mechanical engineers invented very important machinery such as water positive displacement pumps, water and candle clocks and robotics. .
- Some of their pumps were really innovative since they were completely automatic and applied new techniques such as crankshaft-slider, crank-oscillating lever-slider and cam-follower mechanisms.
- Their clocks applied engineering technology baser on water power, mass variation power and mechanical timers.
- The robotics of Al-Jazari were real robotics by today's definition. They were controllable, versatile and more than just a manipulator.

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