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MECHANICAL ENGINEERING IN ANCIENT EGYPT, PART 111: CLOCKS INDUSTRY

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ABSTRACT
The paper is the 111th paper in a series of papers about 'mechanical engineering in ancient Egypt'. It investigates the use of timekeeping devices in ancient Egypt and the design methodology of those devices. Three types of clocks are investigated: water clocks, sundials and star clocks. The problem of constant number of hours per day over the whole year is studied and the optimal design of the water clocks is highlighted. Each type of time keeping devices is supported by a number of typical devices from different ancient Egyptian dynasties.

KEYWORDS: Mechanical engineering in ancient Egypt, time keeping devices (clocks), water clocks, sundials, star clocks.

INTRODUCTION
Ancient Egyptians were really a civilized community could establish one of the great civilizations in the ancient world. During their day and night they were in need to know the time accurately for many purposes either religious or civilian. Because of this they invented a number of timekeeping devices as early as 1500 BC during the New Kingdom of ancient Egypt. They used a number of techniques to record time, but before going inside the details let us review some of the available literature.

Cotterell, Dickson and Kamminga (1986) pointed out that the Court Official 'Amenemhat' served during the reign of Pharaoh Amenhotep I (1525-1503 BC) designed water clocks as accurate as about 15 minutes. They also said that their analysis of the Karnak clock suggested that water clocks of the 18th Dynasty may be used for timing civil nights.[1] Artikelen (1998) analyzed star clocks. He pointed out that star clocks were found in hieroglyphic sources dated to 3000-1000 BC. He investigated two types of ancient Egyptian star clocks and the theory of their operation from the Middle Kingdom (2100-1900 BC) and from the New Kingdom (1189-1077 BC). He outlined that the Rammeside star clock has 25 intervals/15 days for a total of 360 days and 13 stars per interval.[2] Marks (2005) in his chapter about water history and culture outlined that one of the oldest ancient Egyptian water clocks was found in the tomb of Pharaoh Amenhotep I of the 18th Dynasty while the Greeks began using such clocks about 325 BC. His interpretation of the sloping side was to allow water to drip at nearly constant flow rate from the orifice near the bottom.[3]

Barady (2009) derived mathematical models for the flow in a water clock showing that the relation between the water head in the bowl and time is nonlinear.[4] Lambard (2011) presented an early shadow clock dated to 1500 BC and a water clock in the Science Museum of London dated to 1400 BC. Based on a 1996 source, he outlined that the ancient Egyptians marked they water clocks to the 24-hour per day system.[5] Vodolazhskaya (2014) presented the design features of vertical and L-shaped ancient Egyptian sundials with model-development. He marked the hour times from 6 to 12 O’clock. He referred to a sundial dating to the reign of Pharaoh Thutmose III of the 18th Dynasty and a sundial from Faiyum dated to 1000-600 BC in display in the Egyptian Museum of Berlin. He considered in his analysis sundial from the Valley of the Kings at Thebes excavated in 2013 having 155 x 175 mm face dimensions and a 6 mm holes on the sundial rod.[6] Vodolazhskaya, Usachuk and Nevsky (2015) analyzed and interpreted marks and drawings of a water clock from the Bronze Age found in Ukraine. They claimed that it had approximately the same age as the oldest ancient Egyptian water clock. They presented also the oldest Egyptian water clock found in Karnak dated to the reign of Pharaoh Amenhotep III of the 18th Dynasty!!.[7]

Symms (2016) investigated the sundials of the ancient Egyptians and set a catalogue and the results emerging from her investigations.[8] Schomberg (2018) outlined that the investigation of water clocks in Egypt was the best documented development in the history of ancient technology. She added that 3D scans helped to ascertain the knowledge existed about fluid dynamics around 1500 BC. She presented the oldest water clock originated during the reign of Pharaoh Amenhotep III of the 18th Dynasty from outside and inside. She showed that 12 scales (corresponding to 12 months) with hour markings were inscribed on the inside of the vessel and above each scale (on the rim) the name of each month was inscribed.[9] Liavan and Schonberg (2019) investigated the design of ancient Egyptian water clocks between religious significance and scientific functionality. They outlined that in religion, days were structured by hours and the hours served also in protecting rituals for human beings in particular the King and structured many temple rituals.[10] Sonderegger (2020) described the historical development of sundials in Central and Western Europe. He outlined that the history of portable sundials started in ancient Egypt. He presented a sundial from the time of Pharaoh Thutmose III of the 18th Dynasty in display in the Neues Museum of Berlin and displayed also a vertical sundial from the 13th century BC having a semicircle divided into 12 parts with marks indicating half ours.[11]

Hwang, Yan and Lin (2021) examined the historical development of ancient water powered mechanical clocks. They outlined that water clocks were mainly used for astronomical time keeping, for religious rituals, for military affairs, for court litigation timekeeping and for time allocation of water rights. They outlined also that the un-earth of the pot-shaped water clock at the temple of Amun Re at Karnak in 1904 dated to the reign of Pharaoh Amenhotep III of the 18th Dynasty.[12] Elgammal (2022) outlined that the ancient Egyptians relied on stars as timekeepers during night for 360 days per year using ‘decans’ and used ‘triangle decans’ to measure the remaining five days of the year. She outlined also that the ancient Egyptians split the ‘celestial sphere’ into three portions (northern – southern – center in the middle) with 12 pieces per portion producing 36 sections giving the year star weeks. ‘Decans’ represented the 10 days a star spends in the sky before another star appears. Also, she outlined that the ancient Egyptians divided the month into star groups (decans) allowing the measurement of time at night.[13] Wikipedia (2023) wrote an article about ‘water clocks’ outlining the history of the water clock as it was dated to 1417-1379 BC during the reign of Pharaoh Amenhotep III and the oldest documentation of the water clock was a tomb inscription in the tomb of ‘Court Official Amenemhat’. They presented a water clock from late 5th century in display in the ‘Agora Museum’ in Athens.[14]

The Water Clock

The ancient Egyptians invented the water clocks as a time measurement clock capable of measuring time during date and night. The oldest water clock was found in the tomb of Amenhotep I, the second Pharaoh of the 18th Dynasty (1514-1503 BC).[5], [15] This was followed by water clocks from the reigns of Thutmose III (1479-1425 BC)[16], Amenhotep II (1425-1398 BC),[17] Amenhotep III (1388-1350 BC[18] and Dynasty 30 (380-343 BC).[19]

Water Clock from the Reign of Pharaoh Amenhotep II

- This water clock is in display in the Science Museum at London.
- It is shown in Fig.1.[20]

Figure 1: Water clock from the reign of Amenhotep II.[20]

- Material: Carved alabaster.
- Shape: Conical bowl with small base compared with its top edge forming the conical sides.
- Output water flow: Through orifice in the bottom.
- Flow characteristics: The dimensions of the bowl were scientifically selected to avoid nonlinearity of flow through orifices. This will be investigated in some details by the end of this section.
- The external surface of the bowl is decorated by astronomical scenes.
- The internal surface of the bowl is labeled by 12 columns with holes giving the hours during the day (or night) during the 12 months of the year.
- The month name is carved on the top rim of the alabaster bowl.

Water Clock from the Reign of Pharaoh Amenhotep III

- This water clock is in display in the Egyptian Museum at Cairo.
- It is shown in Fig.2.[21]

Figure 2: Water clock from the reign of Amenhotep III.[21]

- The material and characteristics are similar to those of the water clock in Fig.1.
- The rim and outer surface are divided into three horizontal sections with astronomical inscriptions.
- The view shows the false holes on the internal surface indicating the time during 12 months of the year.

Water Clock Fragment from the 30th Dynasty

- This water clock fragment is in display in the Petrie Museum at London.
- It is shown in Fig.3.[19]

Figure 3: Water clock fragment from the 30th Dynasty.[19]

- Material: Carved basalt.
- Shape: Semi-Conical bowl with irregular bottom.
- The outside surface of the bowl is divided into circular strips carved by scenes and hieroglyphs.

Flow Analysis through the Water Clock

- Using fluid mechanics principles, the flow of water through the orifice in the bottom of the partial-conical bowl can be analyzed to relate the head inside the bowl to time.[21,22]
- The dimensions of the water clock used in the analysis are typical for a water clock in the Egyptian Museum of Cairo dated 1415-1380 BC and belongs to Pharaoh Amenhotep III of the 18th Dynasty. They are as follows

➢ Height: 249 mm[23]
➢ Top diameter: 284 mm (estimated)
➢ Bottom diameter: 153 mm (estimated)
➢ Orifice diameter: 1.8 mm (simulated for reasonable maximum discharge time)
➢ Discharge coefficient: 0.86 for a thick plate square orifice.[24]

The flow rate through the orifice in the bottom of the Amenhotep III's water clock is simulated analytically and the relation between the water head and time is derived and presented graphically using MATLAB using its plot command.[25] This plot was generated for three angles of the bowl walls: 10, 14.737 and 20 degrees and shown in Fig.4. Comments:

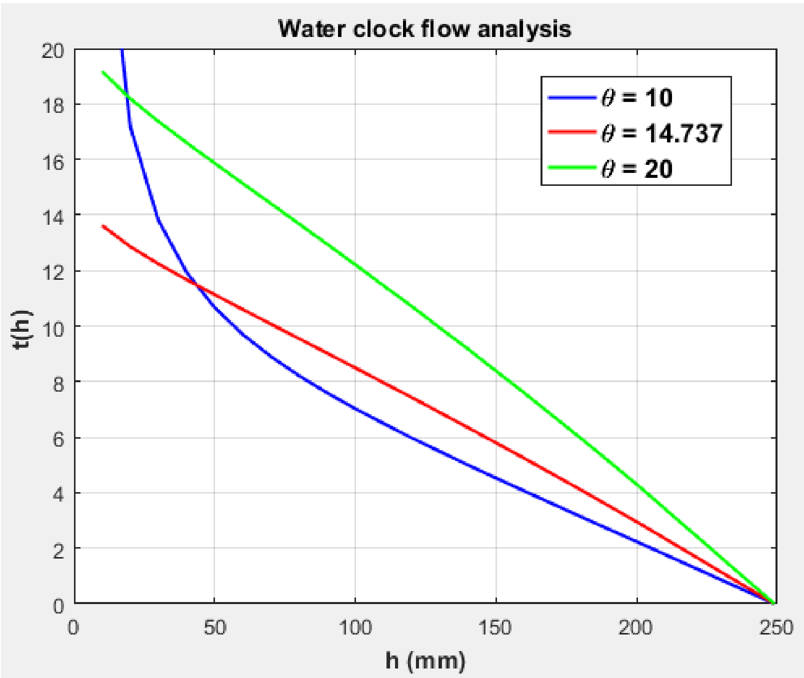

Figure 4: Time-head graphs of Amenhotep III water clock.

- The walls angle 14.737 degrees belongs to the actual wall of Amenhotep III's water clock.

- The walls angle 10 degrees results in t-h nonlinear characteristics. This was practiced also for 12.5 degrees through simulation.
- The walls angles 14.737 and 20 degrees result in t-h linear characteristics which is suitable for the water clock scaling of the time.
- The ancient Egyptians used the 14.737 degrees angle for the bowl sides which means that they knew that less than this value will produce nonlinear characteristics (they were pioneers also in fluid mechanics).
- The total time to discharge the water from the clock is 14 hours which is the longest day during June.[26]

Scaling the time-indicators of the Egyptian water clock

- They knew that every total day has 24 hours.[27]
- Further, they divided every total day to 12 hours day and 12 hours night.[27]
- On the other hand they know well that the time span of day and night changes in all over the year.
- Therefore, they have to device time keeping devices with variable time scale (12 time scales) for the whole year.
- This is what they have done. They used 12 scales on the internal surface of the water clock, one scale per month with small false holes for the 12 hours starting from the top level of the water in the clock-bowl as shown partially in Fig.2.
- A scientific design of the time scales for the whole year using MATLAB graphics is prepared by the author and shown in Fig.5 for the day time. Comments:

➢ The longest time scale is for the longest day during June (red color).
➢ The shortest time scale is for the shortest day during December (red color).
➢ The longest hour is during June and the shortest hour is during December.
➢ The hour span decreases gradually while moving from June in both sides (blue color).

The Sundial Clock

This is the second type of time keeping devices of ancient Egypt. The main feature here is that it depends on the sun light which is shine and visible in most of the days of the year in all areas of Egypt. Most of the literature refers to the time-origin of sundials to the reign of Pharaoh Thutmose III (1479-1425 BC) of the 18th Dynasty.[28] Then, models of such clocks appeared during the reigns of Pharaoh Amenhotep III (1388-1350 BC) of the 18th Dynasty[29] 19th Dynasty (1292-1186 BC)[30], 21st and 22nd Dynasties (1000-800 BC).[31]

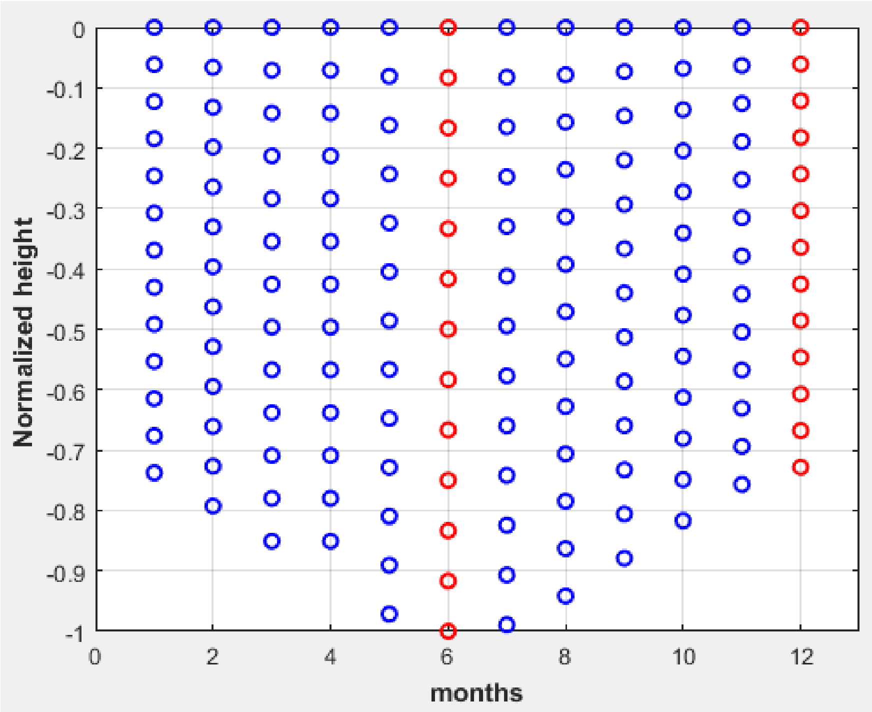

Figure 5: Time scales of the ancient Egyptian water clock day time.

Sundial of Pharaoh Thutmose III

- Thutmose III was the 6th Pharaoh of the 18th Dynasty (1479-1425BC).
- His sundial was of the L-shaped type.
- It is in display in the Egyptian Museum at Berlin.
- Its image is shown in Fig.6.[32]

Figure 6: L-shaped sundial of Thutmose III.[32]

- It has the characteristics[23]
- ➢ Dimensions: 232 x 46 x24 mm.
- ➢ Material: Metamorphic green slate.
- ➢ Markings and inscriptions:
- • Five circular marks on scale.
- • Two holes on top of gnomon.

- The Cartouche of the Pharaoh is inscribed on the extreme end of the horizontal part of the sundial.

Sundial of Pharaoh Amenhotep III

- Amenhotep III was the 9th Pharaoh of the 18th Dynasty (1388-1351 BC).
- His sundial was of the L-shaped type.
- It is in display in the Egyptian Museum at Berlin.
- The image of its gnomon portion is shown in Fig.7.[29]

Figure 7: L-shaped sundial gnomon of Amenhotep III.[29]

- It has the characteristics[23]
- ➢ Dimensions: 46 x 30 x 13 mm.
- ➢ Material: Wood.
- ➢ Jointing with the sundial scale: The gnomon takes the shape of a human being having two legs. The two legs are secured in a lit in the scale bar forming a fixed joint.
- ➢ Markings and inscriptions:
- o The gnomon is inscribed on its front face by a scene for the Pharaoh offering to a Deity.

Sundial of Pharaoh Seti I

- Seti I was the 2nd Pharaoh of the 19th Dynasty (1290-1279 BC).
- His sundial was of the L-shaped type.
- It is in display on his tomb ceiling in Abydos of Egypt.
- The image of his sundial is shown in Fig.8.[32], [33]
- It has the characteristics:
- ➢ Material: Painting.
- ➢ Scaling: The measuring link is divided into 12 sections (section per hour).

- Inscriptions
  - Detailed lengthy inscriptions outline the details of the measured hours.

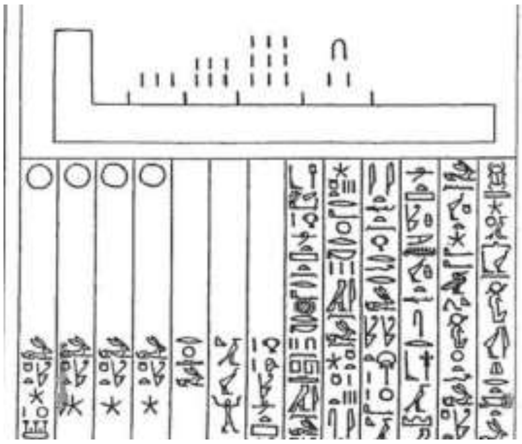

Figure 7: L-shaped sundial in Seti I tomb.[32,33]

Semi-circular Flat *Sundial from the 19th Dynasty*

While carrying out archaeological investigations in the Valley of Kings at Luxor in 2013 by Prof. Susan Bickel and her team from the University of Basel of Switzerland, they found one of the oldest sundials shown in Fig.8.[34]

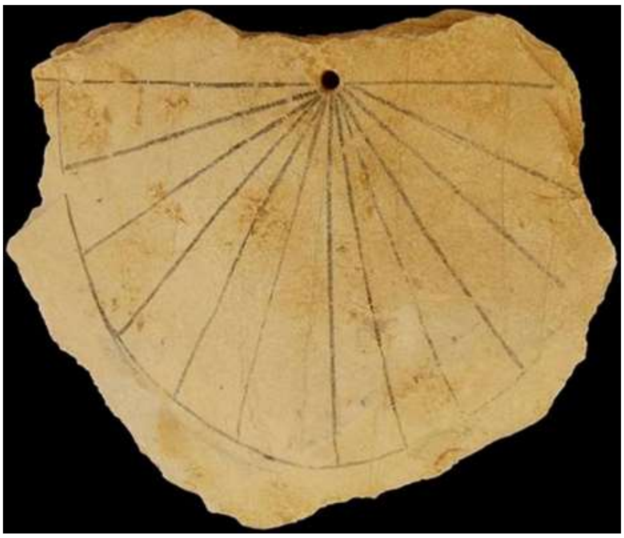

Figure 8: Semi-circular sundial from the 19th Dynasty.[34]

- Period: 19th Dynasty (1292-1186 BC).
- Characteristics[34,35]
  - Material: Limestone.
  - Dimensions: 177.8 x 152.4 x 33 mm.
  - Length of the horizontal time axis: 160 mm.

- Gnomon material: Metal or wood.
- There is a vertical noon-line (y-axis) through the gnomon.
- There are 6 segments in each side of the noon-line giving morning and afternoon hours. This gives 12 hours in a day in the whole year (according their timing strategy).
- They put small dots in the middle of each hour segment for fine timing.
- The 12 hours are seasonally uneven.

- It is well known that the day light length changes from month to another.
- The latitude of Luxor city (ancient Thebes) is 25.687 degrees.[34]
- According to the ancient Egyptian system of time assignment, they fixed the number of hours during day and night. While astronomically the daytime (and nighttime) changes almost daily according to sunrise and sunset. Because we are talking about sundials, only daylight is required. Table 1 gives the hours of daylight in Luxor during one year.[35], [36]

Table 1: Average daylight in Luxor.[35,36]

Month	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Daylight (hr.)	10.7	11.3	12	12.8	13.4	13.7	13.6	13.1	12.3	11.6	10.9	10.6

- According to Table 1, March is the only month having 12 hours daylight with 180 degrees hour-scaling area and 15 degrees interval between the hours.
- The sundial hour-scaling during March is constructed using MATLAB graphics[25] and shown in Fig.9.

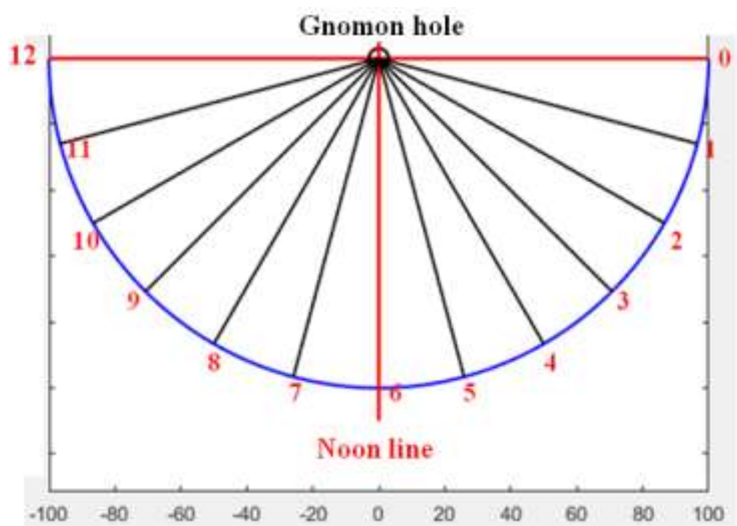

Figure 9: MATLAB sundial hours-scaling during March.

- The gnomon shadow on the sundial gives the time.
- It needs zero adjustment as the sun rises to adjust the shadow to be on the 0 line of the sundial.

The Star Clock

The star clock is one of the ancient Egyptians clocks used during night to know time beside the water clock. This may be the most difficult type to use because it depends on the stars appearance in the sky. This technique for time measurements continued thousands of years. I have seen my father in the 1950’s looking at the sky and telling us the time during night. Here are some of the activities related to this type of timekeeping:

- The word ‘hour’ was mentioned in the pyramids texts before 2400 BC (during the Old Kingdom).[37]
- The star table of Idy from Asyut on the inside surface of his coffin’s lid is an early example of such star tables. The Idy’s coffin lid is in display in the Museum of the University of Tubingen in Germany.[38] Idy lived during the reign of King Mentuhotep III of the 11th Dynasty of ancient Egypt (2009-1997 BC). The Idy’s star table is shown in Fig.10.[39]

Figure 10: Star table of Idy from the 11th Dynasty.[39]

- Comments

➢ It is composed of 12 vertical bounded-columns.

➢ There is a central column exactly in the middle of the table.

➢ The table reflects a complete annual circle with 10 days intervals (decans).

- Each decan contains the names of stars associated with it (12 rows of star names[37]).
- The night is divided by 12 time areas (hours) each assigned by one star.[37]
- In the top of the star table the Egyptian calendar of 10 days/week and 12 months/year of 30 days each is written for 360 days/year.[38]
- A half week of 5 days is written in the year's end in a column in the table's end.[38]
- They listed the star names using hieroglyphic characters in the 12 rows columns.[38]
- Every cell gives the rising/setting of a specific star in the sky.[38]

- The second example of star tables is from the tomb of Senenmut, the Steward of Pharaoh Hatshepsut of the 18th Dynasty (1479-1458 BC) in his tomb in Thebes.
- The astronomical diagram of Senenmut consists of two parts for the northern and southern panels shown in Fig.11.[41]

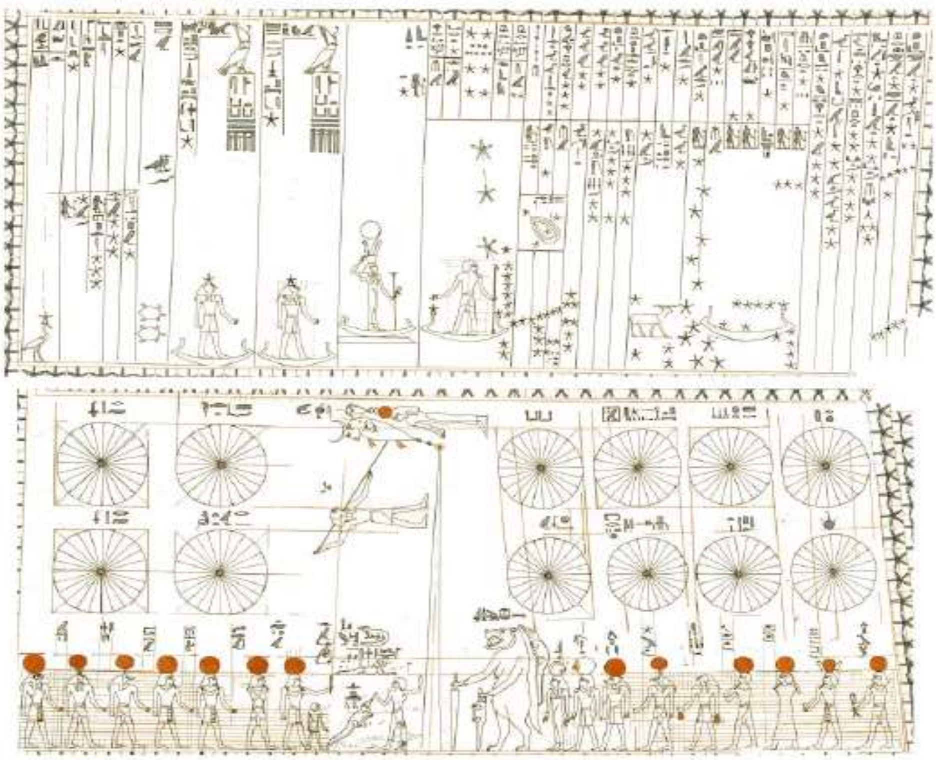

Figure 11: Astronomical diagram of Senenmut from the 18th Dynasty.[41]

- Comments[40,41]

- The diagram shows circular constellations in the form of discs divided into 24 sections (may correspond to 24 hours periods).
- Some of the stars appearing in the diagram are Sirius, Onion, Ursa Major and Draco.
- The four circles in the bottom left refer to the planting season during October to February.

- The eight circles in the right refer to the other two seasons of the ancient Egyptians: season of harvesting (March to May) and season of flooding (June to September).
- The upper parts of the southern panel (top panel) display the names of the decans in separate columns.
- The 12 circles carry the names of the 12 months written over them.
- The decans in the southern panel are connected with the seasonal hours having variable length.
- The 12 circles relate to equal length hours.
- The second example of star tables is from the tomb of Senenmut, the Steward of Pharaoh Hatshepsut of the 18th Dynasty (1479-1458 BC) in his tomb in Thebes.
- The astronomical diagram of Senenmut consists of two parts for the northern and southern panels shown in Fig.11.[41]

- The third example of star tables is from the tomb of Pharaoh Seti I, from the 19th Dynasty (1290-1279 BC) in his tomb in Thebes.
- A part of the ceiling in his tomb is shown in Fig.12.[42]

Figure 12: Astronomical diagram of Seti I from the 19th Dynasty.[42]

- Comments[42]

- The astronomical ceiling is divided into two panels.
- One of the panels has 35 columns.
- The first 23 columns comprise the decans with their stars.
- Column 22 comprises the Onion star.
- Column 18 comprises the Egg star.
- Columns 24-26 comprise the Jupiter, Saturn and Mars stars.
- Columns 34-36 comprise the Mercury and Venus star.

- The fourth example of star tables is from the tomb of Pharaoh Ramses VI, from the 20th Dynasty (1145-1137 BC) in his tomb in Thebes.
- A line diagram of a part of the decorations of his ceiling in his tomb is shown in Fig.13.[43]

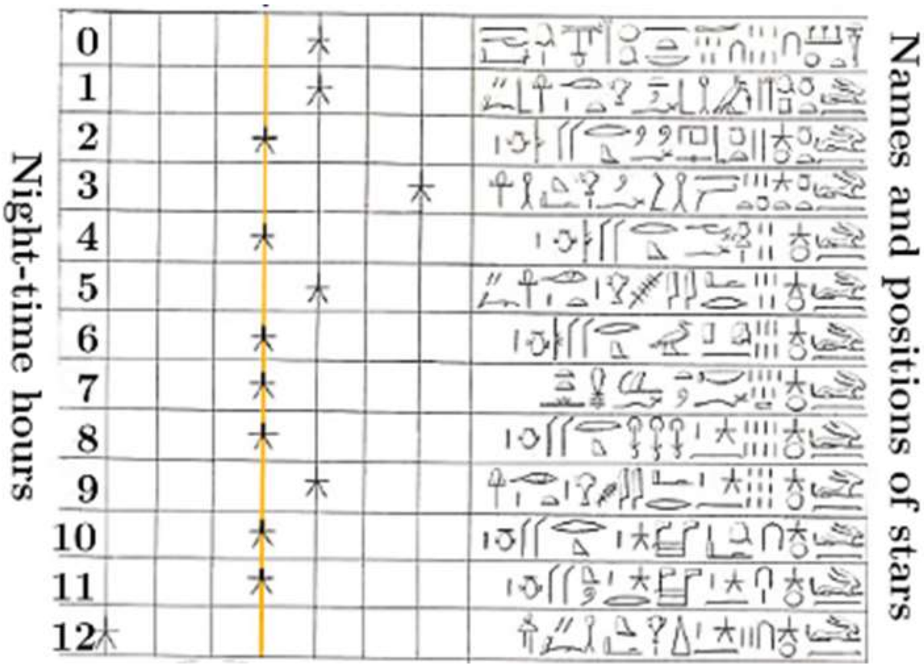

Figure 13: Star clock of Ramses VI from the 20th Dynasty.[43]

- Comments
- ➢ The first column is allocated for the night hours (12 hours) translated to the Arabic numbers.
- ➢ The first hour starts from sun-set.
- ➢ The last hour ends by sun-rise.
- ➢ The information source didn’t show which night in which month.
- ➢ The fourth to seventh columns give the location of the stars in the sky.
- ➢ The last column gives the names and locations of the starts during the specific hour.

CONCLUSION

- This paper is the 111th research paper in a series of papers aiming at the investigation of mechanical engineering in ancient Egypt.
- It handled three tyes of timekeeping devices used by the ancient Egyptians: water clocks, sundials and star clocks.

- It presented typical water clocks from the reign of Pharaohs Amenhotep II, Amenhotep III of the 18th Dynasty and from the 30th Dynasty.
- The ancient Egyptian designer used a clock-bowl with semi-conical sides to achieve high technology fluid mechanics objectives regarding the water flow rhrough the orifice in the bottom of the bowl.
- The author derived the relationship between the head inside the bowl and the elapsed time from the top level for side angles with 10, 14.737 and 20 degrees shown graphically in one graph.
- The t-h graphs depicted the linear characteristics of the t-h relations for both 14.737 and 20 degrees of bowl side's inclination. This outlined the optimal design principle known and used by the ancient Egyptians.
- The paper investigated the concept of constant number of hours (12 hours) per day used by the ancient Egyptians during the whole year. This complicated their designs for the timekeeping devices. The paper investigated the design of the time scales of the water clock over the 12 months of the year.
- The invention of sundials was originated during the reign of Pharaoh Thutmose III of the 18th Dynasty.
- Sundials produced during the reigns of Pharaohs Thutmose III, Amenhotep III (from the 18th Dynasty), Seti I (from the 19th Dynasty) were presented and analyzed.
- Star clocks were the third type of clocks used by the ancient Egyptians through star tables inscribed on coffins and tomb ceilings since the time of the 11th Dynasty.
- The paper presented star tables from the 11th, 18th, 19th and 20th Dynasties.

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BIOGRAPHY

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DEDICATION

I dedicate this research work to the great architect engineer Senenmut from the 18th Dynasty of ancient Egypt because

- He was the '*Steward*' of Hatshepsut, the 5th Pharaoh of the 18th Dynasty (1479-1458 BC).
- He was the Chief Architect of Pharaoh Hatshepsut.
- He supervised the production of the two obelisks of Pharaoh Hatshepsut.
- One of his great projects was the Mortuary and **Architect Senenmut** the Sublime and Sublimes Mortuary Temples of Pharaoh Hatshepsut.
- His tomb had the earliest star map as an astronomical ceiling.
- Senenmut was also an astronomer.
- All the appreciation to the great architect SENENMUT.