Experimental Archaeology: Wise Jar - An Ancient Iranian Invention for Liquid Separation from 5th Century A.H. (9th A.D.)

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After advent of Islam especially through and after the reign of Abbasid caliphs; interest of scientists and engineers was drawn towards the" mechanical or ingenious devices". The wise jar was originally designed by Ahmad ibnMüsä, the famous Iranian scientist who lived in the 5th century A.H.(9th A.D). It consists of a jar with a mechanically intelligent mechanism inside, which is capable of separating two liquids on the bases of their densities. This jar was constructed and tested as a part of an experimental archaeology research project at the Iranian Research Organization for Science & Technology (IROST). The jar was designed in detail, and was manufactured and tested according to a book entitled Al-Hiyal; written by Ahmad ibn Müsä. However, to establish the correct operation of the jar, minor modifications were made to its original design set up and it was tested, and as a result the jar operated as expected by the book.

Keywords: *Banü Müsä; Ahmad ibn Müsä; Al Hiyal; Separating liquids; wise jar*

Introduction

The three sons of *Müsä ibn Shäkir*, *Jafar Muhammad*, *Ahmad* and *al-Hassan* ; mainly known as " *Banü Müsä*" or sons of Müsä; lived during the reign of *Abbasid caliph; al-Ma'mün* (A.D. 813-833) and the other succeeding caliphs . The three brothers played an important role in the development of mathematical science (Hockey *et al.* 2007: 92-24; Pingree 1989: 716-717). The Banü Müsä brothers were among the first group of mathematicians to begin to carry forward the mathematical developments begun by the ancient Greeks. Jaafar Muhammad worked mainly on geometry and astronomy while Ahmad worked mainly on mechanics and al-Hassan worked on geometry (Al-Dabbagh 1970-1990; Brill 1998: 640-641).

Their renown and influence lies not only in their scientific work but also in their special efforts in translating the Greek scientific texts of the Hellenistic period into Arabic at the house of wisdom (Hockey 2007: 92-24; Pingree 1989: 716-717).

The House of Wisdom was a library, translation institute and research center established in Abbasid-era, in Baghdad, Iraq.(Al-Khalili 2011). It was a key institution in the Translation movement and is considered to have been a major intellectual hub during the Islamic Golden Age. The House of Wisdom was founded by Caliph Harun al-Rashid and culminated under his son al-Ma'mun. Later; al-Ma'mun brought many well-known scholars to share information ideas and culture in the House of Wisdom. Many of the most learned Muslim scholars; such as Banü Müsä brothers; were part of this research and educational institute during the 9th to 13th centuries A.D. Besides translating books to Arabic and preserving them, scholars associated with the House of Wisdom also made many remarkable original contributions to diverse fields. (Lyons 2009 ; Meri and Bacharach 2006).

In the early years of the house of wisdom, Mohammad; the oldest brother; and Hassan; the youngest one; played a crucial role in the development of the Islamic mathematics. An important instance of their work was to prepare a translated copy of the Apollonius conics which at the time the available copies were unreliable due to many errors which made them impossible to learn from (Suzuki 2009).

Banü Müsä brothers have not only; translated the Greek text but have also made important mathematical contributions .They were among the first scientists to study the Greek mathematical works and to lay the foundation of the Arabic school of mathematics. Their work; however; deviated from classical Greek mathematics in ways that were very important to the development of some mathematical concepts. The most studied treatise written by the Banü Müsä is *Kitab marifat masahat al-ashkal* (The

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Book of the Measurement of Plane and Spherical Figures). Later this work became well known through the translation into Latin by Gherard of Cremona entitled "*Liber triumfratum de geometr*i" in 12th century A.D. (Dalmedico and Peiffer 2009). The treatise considers problems similar to those considered in the two texts by Archimedes, namely on the measurement of the circle and on the sphere and the cylinder (Sato1985:9-61).

In another aspect, however, the Banü Müsä made a definite step forward. The Greeks had not thought of areas and volumes as numbers, but had only compared ratios of areas etc. The Banü Müsä's concept of number is broader than that of the Greeks. For example they describe π as the magnitude which, when multiplied by the diameter of a circle, yields the circumference (El-Dabbah 1966: 131-139)

In the text areas as described as products of linear magnitudes, so the terminology of arithmetic is perhaps for the first time applied to the operations of geometry. The Banü Müsä also introduces geometrical proofs which involve thinking of the geometric objects as moving. In particular they used kinematic methods to solve the classical problem of trisecting an angle(O'Connor and Robertson 1999 ; Knorr 1990).

There is not precise information on the life of Müsä ibn Shäkir, their father, but one thing is known for certain ,namely that he was a capable and noted astronomer and geometrician who lived and worked in close companionship of al-Ma'mün,the younger brother of the caliph , *Emin* (A.D. 809-813). They were both residing at *Marw* in *Khuräsän* during the caliphate of Emin ; and due to his potentials, Müsä managed to get close to al-Ma'mün whose simple court was the patron of scientists at that time (Hockey 2007: 24-92; Ghazany1993b:1-48). After death of Müsä his three sons lived under care of al-Ma'mün, who entrusted their guardianship to *Ishäk ibn Ibrähim*. Then the famous astronomer and astrologer*; Yahyä ibn Abi Mannsür* ; became their tutor. Thus the Müsä brothers or rather; the BanüMüsä; during their education had the opportunity to study deeply into the subjects whom they had talent and interest (Pingree1989: 716-717). They were taken to Baghdad when al-Ma'mun started his caliphate, and after his death their actual influence started rising up at different caliphs courts (Pingree1989: 716-717; Ghazany 1993b:1-48).

Generally speaking their interest and ability for geometry, ingenious devices, music and astronomy was not always of the same level (Hockey 2007: 24-92; Ghazany1993b:1-48). The most influential of the three; Abü Jaffar Muhammad; is said to have known the works of Euclid and Ptolemy. Ahmed is famous for his technical works and Hassan was a brilliant geometrician (Ghazany 1993b:1-48).

A number of books are known to have been written during the Hellenistic period on the subject of "ingenious devices" which were later followed by some others in the world of Islam. "*Kitäb Al-Hiyal*" is the name of one of these books which was written in Arabic; in the year A.D. 850; at the city of Baghdad (Ghazany 1993a: 158-159; Hill 1989). This book which was written by "Ahmad ibn Müsä ibn Shäkir Khüräsäni" who is known as one of the Archimedean scientists of that era (Rashed1996: 1-16), mainly consists of as many as 100 ingenious mechanical designs (Bir 1990). At present there are three original manuscript versions of this book. The oldest is kept at the Topkapi palace museum in Istanbul, Turkey. The other two are being kept at Vatican, "Bibliotheca apostolica Vaticana", and in Berlin, Germany," Gotha catalogue von Pertsch" (Ghazany 1993b:1-48). During those years the book "Al Hiyal" was very famous and well known to the engineers and scientists of that era (Pingree1989: 716-717).

During the Hellenistic period and through the middle Ages, much interest was drawn towards the "ingenious devices". These mechanical devices mainly worked by the aid of air and water (pneumatic and hydraulic devices, respectively). Design and construction of vessels, cups and jars capable of separating liquids on the bases of their viscosities and, or their densities by applying the principal of siphons or other mechanisms in conjunction, or independently, occupied the minds of scientists and engineers.

The book "Kitäb al- Hiyal" by Ahmed ibn Müsä, mainly consisted of more than eighty of such devices which employ innovative engineering technologies such as one-way and two-way valves able to open and close by themselves, mechanical memories, devices to respond to feedback, and delays. Most of these devices were operated by water pressure (Ehsad 2009: 161–163).

The wise jar is the only one of these devices which is capable of separating liquids on the basis of their densities. The ingenious and unique design of the jar is the main reason for the special attention which has been paid to this device.

However, amongst all jars and vessels presented in the book Al-Hiyal ,only 25 models have practical value and the remaining, mainly formed by ingenious cups and mechanisms, were designed to be used in drinking parties and, or as the act of magicians for puzzling people who were not acquainted with the estate of the engineering art. In these models a limited number of motifs have been used and by the variation of these, various effects have been reached. It can therefore, be accepted that some of the models have never been realized (Ghazany 1993b:1-48; 1993a: 158 – 159). Fig. 1, represents three different objects of the book Al-Hiyal which are capable of separating fluids on the bases of their viscosities (Ghazany 1993b:figs.149, 151,162).

Fig.1: *Three different devices presented in the book Al-Hiyal (After:Ghazany 1993b: figs.149, 151,162).*

The project

Back grounds

Donald Rutledge Hill (1922–1994) was an English engineer and historian of science and technology. Alongside more general works on the history of technology, he wrote works on the history of medieval Arabic science and technology, and translated a number of books such as "The Book of Al-Hyial " by Ahmad ibn Müsä.(Hill 1989).

Also, Professor Atila Bir a Turkish scientist; at the Istanbul University; started his work on determination of the control engineering of the designs of devices presented in the book Al-Hyial in 1980's. Professor Bir's lectures on system and control engineering but this has not prevented him to lecture history of technology and scientific instruments. He presented his works on Banü Müsä in a number of articles and a book (Bir 1990).

In recent years (IROST) embarked upon new experimental archaeology projects at her mechanical engineering research center. The book Al-Hyial was one of the major sources used for selection of innovations and inventions to be studied and reconstructed (Yassi 2009).

Aims

Actually the project can mainly be regarded as an experimental archeology project in which ancient or historical technologies, innovations and inventions achieved; by the Iranian scientists through the history; are revitalized according to the documents remained from the past. According to this aim, a major research project was under taken by the mechanical engineering research center of IROST. For this purpose a number of works of different Iranian scientists belonging to various eras were selected. These objects mainly consisted of mechanical devices, water clocks, leveling devices, jars and vessels, mechanical balances, astronomical devices, fountains and medical devices.

The main objective of this project was; not only a mere reconstruction of some objects belonging to the past, but It actually involved establishing the levels of technology reached by the Iranian scientists, understanding their way of thinking in scientific and technological aspects and possibly benefitting the outcomes of technology achieved by them in today's engineering. Furthermore, one can consider educating engineering students and young scientists, the approach they had; in the past; to engineering design and solving technological problems, as a guide line to today's research activities. Although, appraisal of their works from this view point is out of the scope of this article, yet, the matter; is worthwhile to be paid special attention to; as another outcome of such projects.

The Approach

Generally, selection of an appropriate object for the purpose of reconstruction was a prerequisite to the process. Therefore a close study of the object, its performance, possible applications, constituting parts, materials used to manufacture the object at its original era and methods of reconstruction was performed before a decision was made for final selection of an object.

Then a thorough data collection about the object was undertaken to obtain all the necessary details for redesigning and manufacturing process. Studying all the details of the work from the engineering view point, considering the conceptual aim of the design, its design relation with other works of the same concept, and testing conditions, were the next steps. The design process actually involved preparing the primary drawings of the detailed design of the object, which was followed by manufacturing a working laboratory sample, using simple materials. The replica was then tested to appraise its operability according to the book. In the case of malfunctioning of the sample, the obstacles responsible for the malfunction were detected and possible solutions were presented, keeping the original design and its concept intact. After finalizing the design, the final master drawings were generated and the work piece was actually manufactured accordingly. Two samples were reconstructed; one of the samples was used for the exhibition, and the other for representing the operating mechanism.

The Wise Jar

The wise jar is one of the most outstanding innovations of Ahmad ibn Müsä ibn Shäkir Khüräsäni amongst the one hundred ingenious designs presented in the book Al-hiyal. The reason for its importance is the fact that; amongst all the jars which have been presented for separation of liquids, the wise jar is the only one which has been designed for separating liquids on the basis of their densities, whereas the rest of the jars presented in the book can perform liquid separation on the basis of the viscosity of the liquids. The unique design of the wise jar is more complicated than the other liquid separating jars. Also, unlike the other devices, preparing the jar for correct operation requires some engineering knowledge.

Definition

According to the hand written versions of the book " Al-Hiyal"; being kept in the museums, Topkopy and Vatican and with reference to the fig.2 the detailed design and operating process of the jar may be defined as follows(Bir 1990; Hill 1989; Ghazany1993b:1-48):

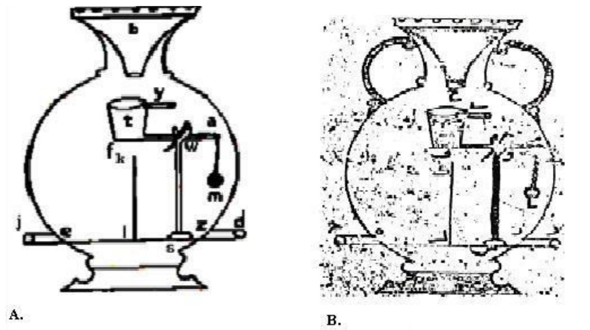

Fig.2: *Drawings of the wise jar (After: Ghazany, 1993b:fig. 74);* ***A)*** *Reconstructed picture of the wise jar;* ***B)*** *Actual drawing of the wise jar.*

Detail Design of the Jar

Generally, the design of the jar may be divided into two parts, the jar and the liquid separating mechanism. The following describes these two parts in detail:

1)The jar consists of two parts, the neck and the bottom, which are of cylindrical and spherical shapes, receptively. The neck is closed at the top with an upside down cone with a hole at the lower end (fig. 3, cone "b", and fig. 4). The jar is made of glass so that it would be possible to see the inside mechanism. The fluid poured into the cone is directed towards the center of the bottom part of the jar. The bottom part of the jar is divided into two separate caches by a cross thin wall, (fig. 2A, line "lk").

2) A vertical high support;(fig. 2A, line "SW"); is fixed to the bottom of the jar and close to the separating wall, or else in between the two small outlet cones(fig. 4A).

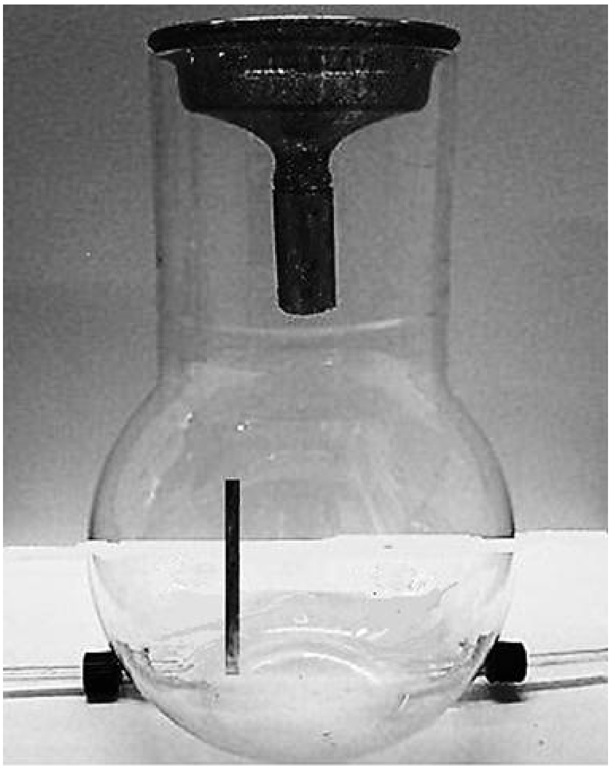

Fig.3: *Reconstructed jar, inlet and outlet cones.*

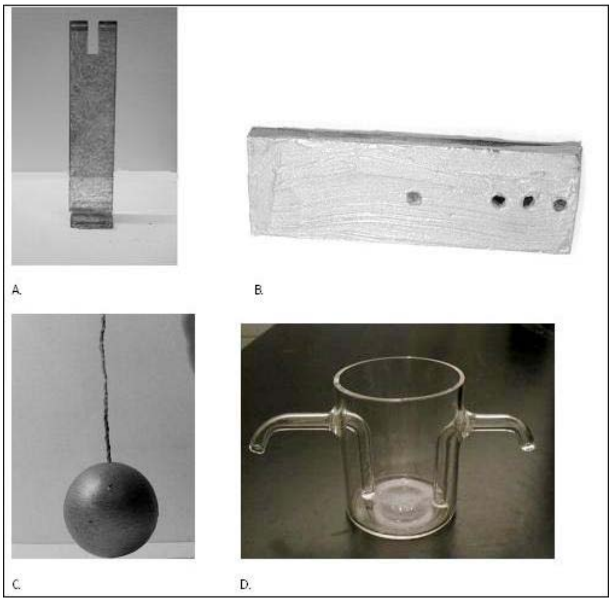

Fig. 4: *The constituent parts of the liquid separating mechanism.* ***A)*** *The vertical high support;* ***B)*** *The balancing rod;* ***C)*** *The balancing bulb;* ***D)*** *The cup.*

3) A balancing rod (fig.2A, part "fa"), which can tilt around a pin (W), is installed at the top of the vertical support (fig. 4B).

4)A balancing bulb, of mass (m), is suspended at one end of the balancing rod, see fig. 4C. Since the jar is always used for separating only two liquids at each test, then, it should be noted that the mass (m) of the bulb should be predetermined according to the densities of the two liquids under test. However, engineering and mathematical calculations are required for determination of the correct amount for the mass of the bulb.

5) At the other end of the balancing rod a cup is installed, into which the liquid is poured via the entrance cone (fig. 2A, cup "t".)As shown in fig. 4D two simple siphon pipes are installed at each side of the cup to ease complete discharge of the cup. This type of siphon has repeatedly been used by Ahmadibn Müsä in various designs in the book Al- Hyial.

When the cup is filled up with the liquid, the balancing bar is tilted, therefore the liquid inside the cup rises above the exit of the siphon pipe and so the siphon is activated and the liquid would flow through the siphon pipe into the related small cone, and thereafter outside the jar. Fig.5 represents the overall assembly of the reconstructed fluid separating mechanism.

Concept of the Operation of the Jar

As stated by the book Al-Hyial, the liquid poured into the jar would flow through the cone into the cup "t", (fig. 2A).The cup is then emptied into the right hand side cache through the pipe "y", (fig. 2A). It is suggested by the book that; the side towards which the balancing rod tilts is determined by the difference between the mass (m) and the sum of the masses of the cup and the liquid poured into it. If the mass of the bulb is lighter than the sum, then the rod would tilt anti-clockwise, towards the left hand side cache, otherwise the rod would tilt clockwise, towards the right hand side cache. Taking that into account that, mass is a function of density, then it could be deducted that, it is the density of the liquid which determines the tilting direction of the balancing rod; which would in turn mean that, the jar can separate liquids according to their densities.

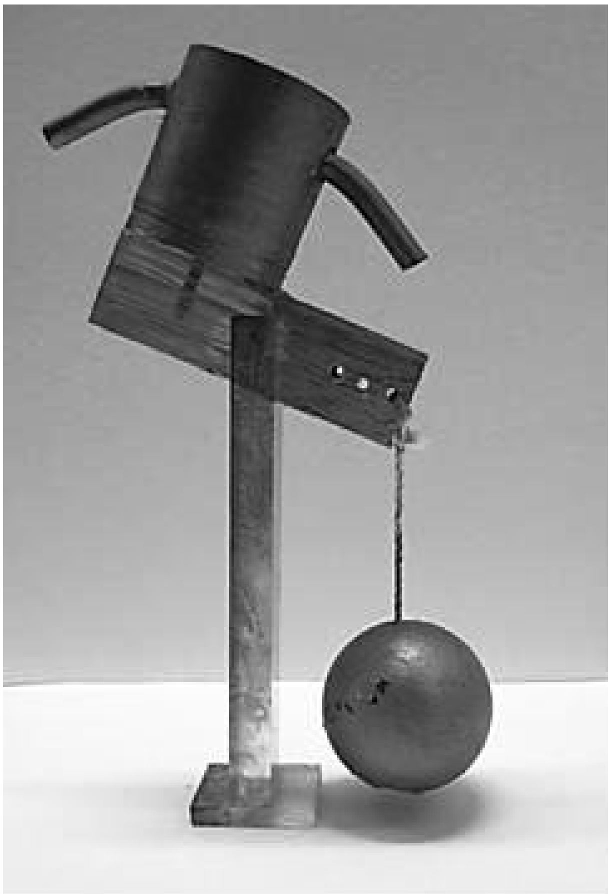

Fig. 5: The assembled fluid separation mechanism.

In the book Al-Hiyal, two liquids; namely oil and water; have been selected for testing the jar. When pouring oil into the entrance cone (the jar);due to the lower density of the oil in comparison with the density of water; the balance rod tilts towards the mass (m),(which has already been determined for separation of oil and water), and empties the oil into the right hand side cache, (fig. 2A). However, if the oil is substituted by water then the balance rod tilts towards the left hand side cache and empties the water into that section. Therefore the jar can decide where to empty the fluids by the virtue of their densities (Bir 1990; Ghazany 1993b:1-48; Al-Khalili 2011).

Malfunctioning of the Design

Initially, in order to validate the original design, the jar was tested according to the set up shown in the original manuscripts (figs. 2A and 2B).For this purpose two liquids of different densities; namely oil and water; were poured into the jar. However, the results indicated that the proposed set up of the separating mechanism did not operate as suggested by the book.

In order to detect the reasons for the malfunctioning of the jar, studying the concept of the design of the mechanism was essential. Fig. 6 shows the simplified conceptual design of the separating mechanism, drawn on the basis of the Balance rod setup suggested by the book Al-Hiyal (fig. 2A).

As maybe observed in Fig. 10, at this stage the balancing bar (p) is in perfect equilibrium, and therefore pouring any liquid into the cup (t) shifts the balance of the rod (P) towards the left hand side

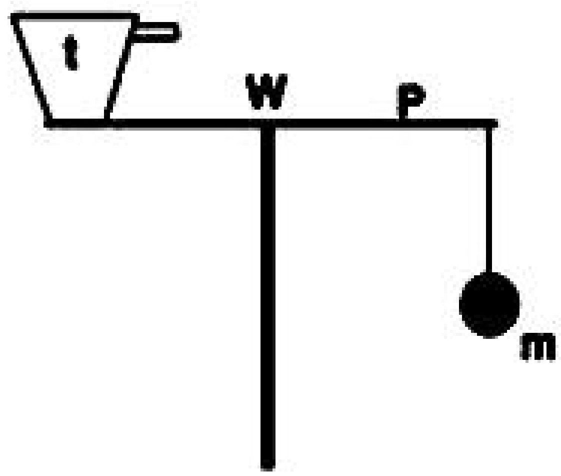

Fig. 6: Balance rod setup according to the book Al-Hiyal.

cache, regardless of the mass, density and the nature of the liquid. When the cup is emptied, the rod (p) will return to equilibrium. Now if another liquid is poured into the cup, the same action will take place in the same direction, and the liquid would; again; be emptied into the left hand side cache. It is evident that the above mechanism will not be practical as it does not fulfill its original purpose.

However, if the system; is set in an off-balance condition at the beginning of the test, meaning that, the rod (P) set to stand tilted towards the mass (m) before pouring the liquid into the cup (t),then pouring the less dense liquid (namely oil) into the cup will not change the state of the bar as shown in fig. 7 for the initial proposed state.

As a result the oil would fill up the cup and would run through the outlet into the right hand side cache. This is because the mass (m) has been so

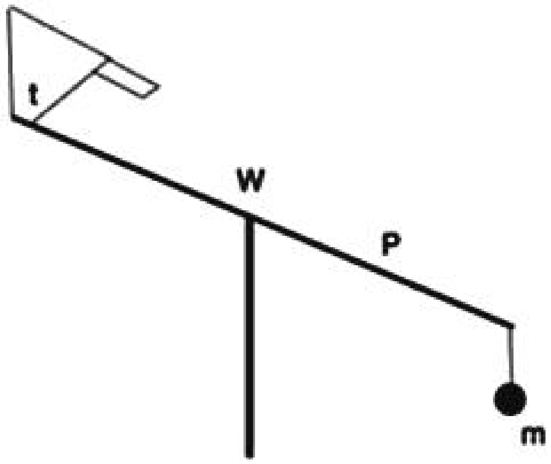

Fig.7: *The balance rod setup at the initial state.*

predetermined that the total mass of the oil and the cup (t) would not overcome the mass (m) (fig. 8).

Now, back to the primary unbalance state shown in fig. 4, if water(namely the denser liquid) is poured

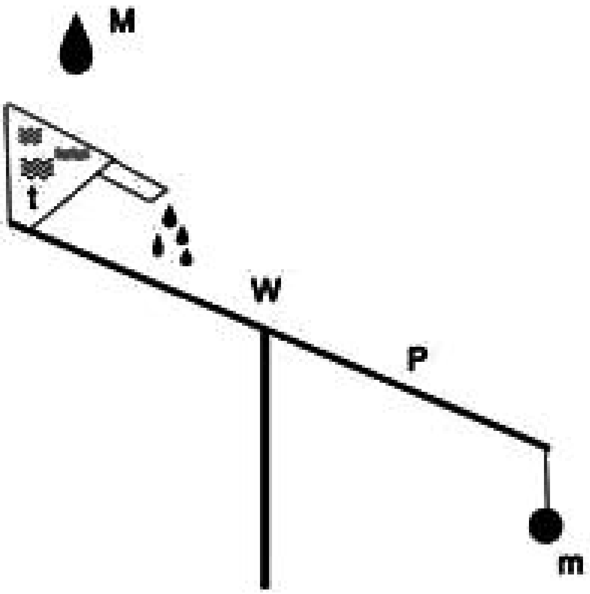

Fig.8: *Pouring oil into the right hand side cache.*

into the cup (t), as the height of water increases inside the cup, the sum of the mass of water and the cup (t) approaches the mass (m). This is due to the fact that a certain volume of water is heavier than the same volume of oil, due to higher density of water. As a result, the rod (p) would tilt slowly back to equilibrium (fig. 9 A).

By pouring more water into the cup, the balanced condition of the rod would deteriorate and the rod(P) would tilt towards the cup (t) and water would be emptied into the left hand side cache of the jar, as shown in fig. 9 B.

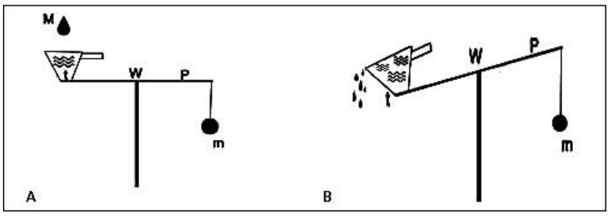

Fig.9: *Stages of pouring water into the left hand side cache;* ***A)*** *State of equilibrium while pouring water into the cup;* ***B)*** *Overcoming the mass of the bulb by the mass of the cup full of water.*

Of course by keeping the values of the mass and the volume of the cup (t) fixed, determination of the value of the mass (m) with respect to the densities of the two liquids under consideration will be possible through mathematical calculations.

As a result, by applying minor modifications to the final setup of the jar mechanism, as described above, the jar would operate as expected and according to the design presented in the book Al-Hiyal.

Conclusion

Many tests with different liquids of various densities were performed on the jar; the results of all tests were in complete agreement with what was expected of the jar according to the book "Al Hiyal". Therefore when a light density liquid is poured into the jar it flows out of the right hand side exit of the jar and the higher density liquid flows out of the left hand side exit of the jar.

Therefore it may be concluded that, The wise jar; originally designed by "Ahmad ibn Müsäibn Shäkir Khuräsäni "; with the ability of separating different liquids according to their densities can operate with minor modifications in its original set up .These modifications change the set up of the inside mechanism of the jar as shown in fig. 10. A comparison of Figure 10, with the original design (fig. 2A), confirms that the basic design of the jar remains intact while only minor modifications of the set up make the mechanism more manageable and successful. Needless to mention that without these modifications the jar would not operate properly.

Therefore the ultimate shape of the jar and its inside mechanism at the start of each test would be as shown in fig. 10.

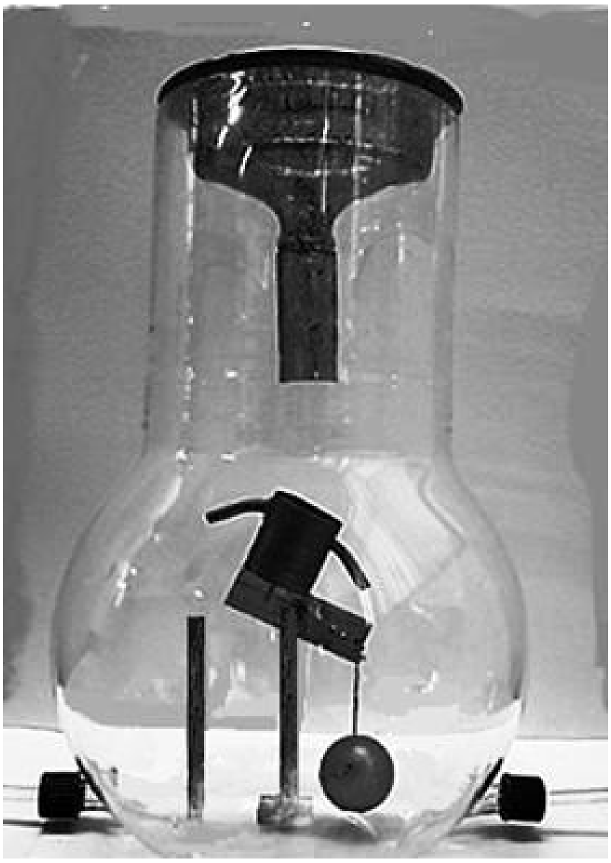

Fig.10: *Photograph of the reconstructed wise jar with the ultimate set up of separating mechanism.*

Generally to obtain the correct operation of the jar, as meant by the original designer; "Ahmad ibn Müsäibn Shäkir Khuräsäni"; some parameters are of paramount importance and should be taken into account. These parameters are as follows:

1- The mass of the balancing mass (m), with respect to the sum of the masses of the cup and its inside liquid.

2- The distance of the line of action of the balancing mass (m) to the tilting point (W) of the balance rod.

3- Setup of the jar mechanism, as suggested by fig. 10.

Fig. 10 represents a photograph of the actual reconstructed jar and the ultimate set up for the liquid separating mechanism.

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