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The Magic Jar and Other Devices from 9th Century Persia

A Historical and Experimental Study

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Abstract

After the advent of Islam the interest of scientists was drawn towards "ingenious devices." Ahmad ibn Müsä ibn Shäkir Khuräsäni was one of the greatest Iranian scientists of the 9th century AD. He worked on many mechanical, hydraulic and pneumatic devices and presented his inventions in a book entitled *Kitäb Al-Hiyal*. A combined historical and experimental research project was undertaken by the Iranian Research Organization for Science and Technology (IROST). One part of the project consisted in designing and reproducing the mechanisms for separating liquids described in *Al-Hiyal*. This paper provides details of the design of four of these devices, which function on the basis of the relative viscosities or densities of the liquids being separated. They were recreated and tested in accordance with the indications provided in ibn Shäkir Khuräsäni's text. This paper provides the historical background and a technical analysis of these remarkable inventions.

Keywords

Banü Müsä – Al-Hiyal – separating liquids

1 Introduction

Jafar Muhammad, Ahmad, and al-Hassan, who are generally known as the Banü Müsä or the sons of Müsä, lived during the period of the Abbasid caliph Abu Jafar al-Ma'mün ibn Harun (786–833 AD) and his successors. The three sons of

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Müsä ibn Shäkir Khuräsäni played an important role in the development of the mathematical sciences.[1]

There is little precise information on the life of Müsä ibn Shäkir, but one thing is known for certain, namely that he was a capable and noted astronomer and geometrician who lived and worked closely with al-Ma'mün, the younger brother of the caliph Emin (809–813 AD). They both resided at Marw in Khuräsän during the caliphate of Emin, and due to his outstanding abilities Müsä managed to win favor with al-Ma'mün, whose modest court sponsored the work of the scientists of the period.[2] After the death of Müsä, his three sons lived under the care of al-Ma'mün, who entrusted their guardianship to Ishäk ibn Ibrähim. Subsequently the famous astronomer and astrologer Yahyä ibn Abi Mannsür became their tutor.[3] In this way the Banü Müsä brothers had the opportunity to pursue in-depth studies of subjects in which they had aptitude and interest.[4] They were taken to Baghdad when al-Ma'mün began his caliphate, and after his death became influential figures at the courts of different caliphs.[5]

The renown of the Banü Müsä brothers was based not only on their scientific work, but also on the special effort that they devoted to translating the scientific texts of the Hellenistic period into Arabic.[6] They were among the first mathematicians to recover and carry forward the developments initiated by the ancient Greeks. Jafar Muhammad was interested primarily in geometry and astronomy, while Ahmad devoted himself to mechanics and al-Hassan to geometry.[7]

The Banü Müsä brothers therefore did not limit themselves to translating and studying the original Greek texts; they also made their own significant contributions to the field, laying the foundations for the Arabic school of math-

1 Thomas Hockey et al., *Biographical Encyclopedia of Astronomers* (New York: Springer Reference, 2007), pp. 92–24; and David Pingree, *Encyclopaedia Iranica*, Vol. III (London, Boston: Routledge & Kegan Paul, 1989), pp. 716–717.

2 Hockey, *Biographical Encyclopedia* (cit. note 1), pp. 92–24; and *Al-Hiyal or the Ingenious Devices*, edited and translated by Sarfaraz Ghazany (Tehran: Beh Nashr Co., 1993), pp. 1–50.

3 Ghazany, *Al-Hiyal* (cit. note 2), pp. 1–50.

4 Pingree, *Encyclopedia Iranica* (cit. note 1), pp. 716–717.

5 Pingree, *Encyclopedia Iranica* (cit. note 1), pp. 716–717; and Ghazany, *Al-Hial* (cit. note 2), pp. 1–50.

6 Ghazany, *Al-Hial* (cit. note 2), pp. 1–50; and Atilla Bir, *Kitäb Al Hial Studies and Sources on the History of Science* (Istanbul: IRCICA Research Center for Islamic History, Art and Culture, 2009).

7 J. Al-Dabbagh, *Banü Müsä*, in *Dictionary of Scientific Biography*, Vol. 1 (New York: 1970); and *Encyclopedia of Islam*, Vol. VII (Leiden: Brill, 1998), pp. 640–641.

ematics. Their work, however, diverged from classical Greek mathematics in ways that were important to the development of certain mathematical concepts. The treatise by the Banü Müsä brothers that has received the most attention from scholars is *Kitab marifat masahat al-ashkal* (*The Book of the Measurement of Plane and Spherical Figures*). In the 12th century this work was introduced to the West through a Latin translation by Gherard of Cremona entitled *Liber triumfratum de geometri*.[8] The treatise considers problems similar to those addressed in two texts by Archimedes, one on the measurement of the circle and the other on the sphere and the cylinder.[9]

In another regard, however, the Banü Müsä brothers made a definite step forward. The Greeks had not thought of areas and volumes as numbers; they only compared their ratios. The Banü Müsä brothers' concept of numbers was much broader; for example, they described π as the magnitude which, when multiplied by the diameter of a circle, yielded its circumference.[10]

The scientific interests of the three brothers and their personal aptitudes for areas ranging from geometry to astronomy and ingenious devices to music differed considerably.[11] The most influential of the three, Abü Jaffar Muhammad, was reputed to have been familiar with the works of Euclid and Ptolemy. Ahmed was famous for his technical inventions, while Hassan was a brilliant geometrician.[12]

Kitäb Al-Hiyal or the *Book of Ingenious Devices* was written by Ahmad ibn Müsä ibn Shäkir Khüräsäni in the city of Baghdad in the year 850 AD.[13] The book was commissioned by the Abassid caliph, Abu Jafar al-Ma'mün ibn Harun, who had previously charged the Banü Müsä brothers with gathering copies of all the Hellenistic texts preserved in monasteries and by scholars since the decline and fall of Roman civilization.[14] The brothers invented a number of

8 Amy Dahan Dalmedico, Jeanne Peiffer, Sanford Seagal, *History of Mathematics: Highways and Byways*, (Mishawaka, USA: Mathematical Association of America, 2009).

9 Tohru Sato, "Quadrature of the surface area of a sphere in the early Middle Ages – Johannes de Tinemue and Banü Müsä," *Historia Scientiarum*, 1985, *28*:9–61.

10 Al-Dabbagh, *Banü Müsä* (cit. note 7), pp. 640–641.

11 Hockey et al., *Biographical Encyclopedia* (cit. note 1), pp. 92–24; Ghazany, *Al-Hiya* (cit. note 2), pp. 1–50.

12 Ghazany, *Al-Hiyal* (cit. note 2), pp. 1–50.

13 Sarfaraz Ghazany, "A word about the book *Al-Hiyal*," International Conference on Science & Technology of the World of Islam, Tehran University, 1993, pp. 158–159 (in Farsi); and *The Book of Ingenious Devices*, edited and translated by Donald Routledge Hill (Islamabad, Pakistan: Hijuga Council, 1989), pp. 7–18.

14 Mark E. Rosheim, *Robot Evolution: The Development of Anthrobotics* (New York: Wiley-Interscience, 1994), pp. 9–10.

automata (automatic machines) and mechanical devices, which they describe in *Al-Hiyal*.[15] Some of these inventions were inspired by the works of Hero of Alexandria[16] and Philo of Byzantium, as well as by ancient Persian, Chinese and Indian engineers.[17] However, many of the other devices described in the book constitute original inventions.[18]

Although the Banü Müsä brothers took Greek works as their starting point, they went "well beyond anything achieved by Hero or Philo." What distinguished them from their Greek predecessors was their specific interest in automatic mechanisms that incorporated "self-operating valves, timing devices, delay systems and other concepts of great ingenuity."[19] Many of their innovations involved complicated applications of both pneumatics and aerostatics.[20] The closest modern parallel to their work lies in control engineering and pneumatic instrumentation.[21] In turn *Al-Hiyal* was later cited as an influence on the work of Al-Jazari, who produced a similarly titled book in 1206.[22] Given that the *Book of Ingenious Devices* circulated widely across the Muslim world, some of its ideas may well have reached Europe through Islamic Spain, such as the use of automatic controls in later European machines or the application of conical valves in the work of Leonardo da Vinci.[23]

There are three original manuscript versions of *Al-Hiyal* extant.[24] The oldest is to be found in the Topkapi Palace Museum in Istanbul, Turkey.[25] The other two manuscripts are conserved in the Bibliotheca Apostolica Vaticana and in the von Pertsch collection in Berlin.[26]

Al-Hiyal quickly became quite celebrated and all the engineers and scientists of the era were familiar with it.[27] The author, Ahmad Banü Müsä, was an adher-

15 Hill, *The Book of Ingenious Devices* (cit. note 13), p. 44.

16 Bryan Bunch, *The History of Science and Technology* (Boston: Houghton Mifflin Books, 2004), p. 107.

17 Hill, *The Book of Ingenious Devices* (cit. note 13), p. 21.

18 Hill, *The Book of Ingenious Devices* (cit. note 13), pp. 13, 19, 23.

19 Hill, *The Book of Ingenious Devices* (cit. note 13), p. 23.

20 Hill, *The Book of Ingenious Devices* (cit. note 13), p. 23.

21 Hill, *The Book of Ingenious Devices* (cit. note 13), p. 24.

22 Hill, *The Book of Ingenious Devices* (cit. note 13), p. 22.

23 Hill, *The Book of Ingenious Devices* (cit. note 13), p. 22.

24 Ghazany, *Al-Hiyal* (cit. note 2), p. 42.

25 Topkapi Sarayi Muzesi Mudurlgu.

26 Hill, *The Book of Ingenious Devices* (cit. note 13), pp. 7–18; and Ghazany, *Al-Hiyal* (cit. note 2), pp. 1–50.

27 Pingree, *Encyclopedia Iranica* (cit. note 1), pp. 716–717.

ent of the Archimedean school[28] and his text is primarily devoted to describing nearly one hundred ingenious mechanical devices designed by himself and his brothers,[29] which were powered by air or water – in other words, functioning pneumatic and hydraulic devices. More than eighty of them involved innovative engineering technologies such as one-way or two-way valves that could open and close automatically, mechanical memories, and feedback and delaying devices, most of them operating by water pressure.[30]

A number of the mechanisms presented in the book were designed to keep liquids of different viscosities and/or densities separate. Most functioned by pouring two liquids into a jar through a single inlet and allowing them to exit through carefully positioned outlets. The outflow of the liquid was controlled by an ingenious device constructed inside the jar that functioned on the basis of the density or viscosity of the liquid.

To gain a clearer understanding of the design of these vessels and to obtain a comparative view of them from an engineering perspective, a research project was undertaken by the Mechanical Engineering Research Center of IROST. The principal objective of this project was to study the design of the inventions presented in *Al-Hiyal* in order to appreciate their underlying engineering principles and to reproduce exemplars in exact accordance with the original designs.

It may be noted that among the jars and vessels described in *Al-Hiyal*, only twenty-five models have practical applications;[31] the remainder consist for the most part of mechanisms such as ingenious cups designed to entertain guests at drinking parties or devices that could be employed by magicians to mystify spectators not acquainted with the engineering arts. The models were based on a relatively limited number of principles, with different effects being obtained through variations on these motifs. It can therefore be assumed that some of the designs were never actually realized.[32]

In the following sections we will describe and compare four of the liquid-separating devices presented in *Al-Hiyal*. The mechanisms for three of them constitute ingenious variations on a single principle and exploit the differing flow rates of liquids with different viscosities in order to keep them separate when they are poured into a single vessel. Another device – which the author

28 Roshdi Rashed, "Archimedean learning in the middle Ages, the Banü Müsä," *Historia Scientiarum*, 1996, *6*:1–16.

29 Bir, *Kitäb Al Hiyal* (cit. note 6).

30 Masood Ehsad, *Science and Islam: A History* (London: Icon Books Ltd., 2009), pp. 161–163.

31 Bir, *Kitäb Al Hiyal* (cit. note 6).

32 Bir, *Kitäb Al Hiyal* (cit. note 6); and Ghazany, "A word about the book *Al-Hiyal*" (cit. note 13), pp. 158–159.

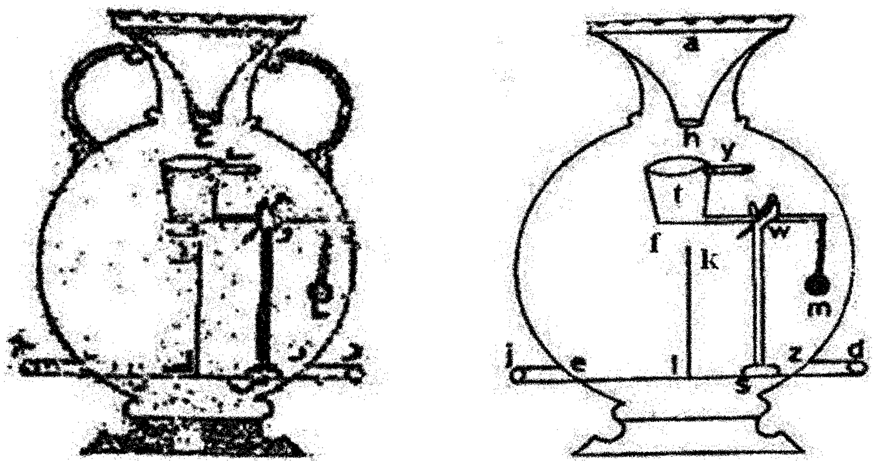

FIGURE 1 (*a*) *Original diagram from Al-Hiyal; and* (*b*) *an exact modern reconstruction of the magic jar. See Ghazany, Al-Hiyal* (*cit. note 2*)*, p. 299.*

termed the “wise” or “magic” jar – deserves special attention because of its unique and innovative design; it is the only one that separates liquids on the basis of their densities.

1 The Magic Jar

1.1 *Description*

Based on the manuscript versions of the book *Al-Hiyal* conserved in the museums of Topkapy and the Vatican, the design and functioning of the magic jar may be described as follows (Fig. 1).[33]

The jar consists of two parts – a cylindrical neck and a large spherical base. The neck is closed at the top by a cone fitted at its lower end with a pipe. The pipe is designed to funnel the fluid that is poured into the cone in a controlled manner down into the jar, which is divided into two caches by a thin wall. The liquid-separating device consists of a vertical support fixed to the bottom of the jar, close to the separating wall, on which a balancing rod that can tilt freely around a pin (w) has been installed. A counterbalance of weight (m) is suspended at one end of the balancing rod and a cup of weight (t) is attached to

33 Ghazany, *Al-Hiyal* (cit. note 2), pp. 1–50; Bir, *Kitäb Al Hiyal* (cit. note 6), and Hill, *The Book of Ingenious Devices* (cit. note 13), pp. 7–18.

the other end. The jar can be used to separate and store two different liquids at a time, with the weight (m) being precisely calculated in relation to the densities of the two liquids. A horizontal pipe (y) attached to the rim of the cup allows the contents of the latter to empty into the right-hand cache.

The side towards which the balancing rod and cup will tilt is determined by the difference between the weight of the counterbalance (m) and the sum of the weight of the cup (t) and the weight of the liquid being poured into it. If (m) is lighter than the combined weight of the cup (t) and the liquid, the rod will tilt in an anti-clockwise direction towards the cache on the left-hand side. If (m) is heavier than (t) plus the liquid, rod will tilt clockwise towards the cache on the right-hand side. Since weight is a function of density, it can be deduced that the density of the liquid will determine the direction in which the balancing rod will tilt. Therefore, the jar can separate liquids according to their densities.

The author of *Al-Hiyal* recounts that he selected two liquids – oil and water – to test the mechanism of the jar. When oil was poured into the jar, it flowed through the funnel into the cup. Because the density of oil is lower than that of water, the balancing rod tilted towards the counterbalance (whose weight had been carefully calculated for the separation of oil and water), and emptied the oil into the right-hand cache. When water was poured into the jar, the balancing rod instead tilted towards the left-hand cache and emptied the contents of the cup into it.[34] Thus, if the mechanism could not be seen by the viewer, it would appear that the jar 'magically' kept the two liquids separate.

1.2 *The Malfunctioning of the Design*

If the jar is reconstructed in accordance with the original design, as shown in Figure 1b, it is clear that any fluid poured into the cup will unbalance the rod and cause it to tilt towards, and empty its contents into, the right-hand cache regardless of the density of the liquid.

We determined that a modification would correct this error in the original design – that is, the weight (m) should be carefully selected so that the device is off balance at the outset, with the rod (P) slightly tilted towards the weight (m). In this case, when the less dense liquid is poured into the jar it will invariably spill out of the cup into the right-hand cache, because the weight of the liquid (M) cannot overcome the weight of the counterbalance (m) (Fig. 2a). However, when a denser liquid is poured into the cup, as the volume of liquid increases the combined weight of the liquid and the cup (t) will approach that of the

34 Ghazany, *Al-Hiyal* (cit. note 2), pp. 1–50; Bir, *Kitäb Al Hiyal* (cit. note 6), and Hill, *The Book of Ingenious Devices* (cit. note 13), pp. 7–18.

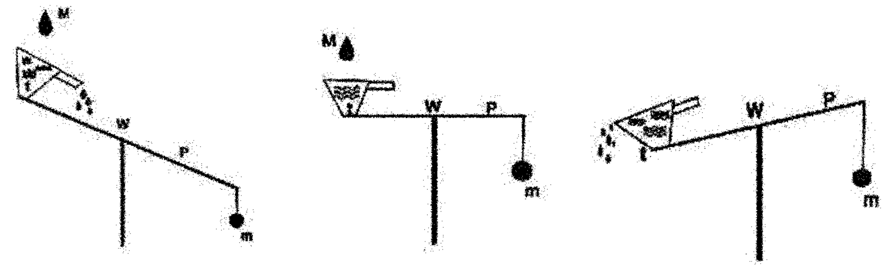

FIGURE 2 *The functioning of the modified liquid-separation device, in which the resting position of the balancing rod is not in perfect equilibrium: (a) the cup when filled with the less dense liquid tilts toward the right-hand cache; (b) the equilibrium point is reached when the cup is partially filled with the denser liquid; (c) the cup tilts toward the left-hand cache when completely filled with the denser liquid.*

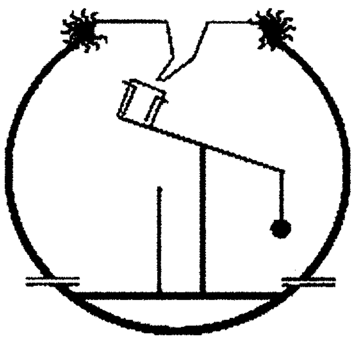

FIGURE 3 *The first phase of the liquid separation process in our modified version of Ahmad ibn Müsä's magic jar.*

counterweight (m) and, assuming the friction at point (W) is minimal, the rod (P) will first return to the horizontal position as the equilibrium point is reached (Fig. 2b) and then, as more water is poured and the system becomes increasingly unbalanced, tilt to the other side so that when the cup is filled it will empty into the left-hand cache of the jar (Fig. 2c).

In short, if the weight and the volume of the cup (t) are known and kept constant, the appropriate value for the weight (m) with respect to the densities of the two liquids being tested can be calculated. Therefore, we would propose that if the original set-up of Ahmad Banü Müsä's magic jar (Fig. 1b) is modified to the configuration shown in Figure 3, it will work as its inventor had intended.

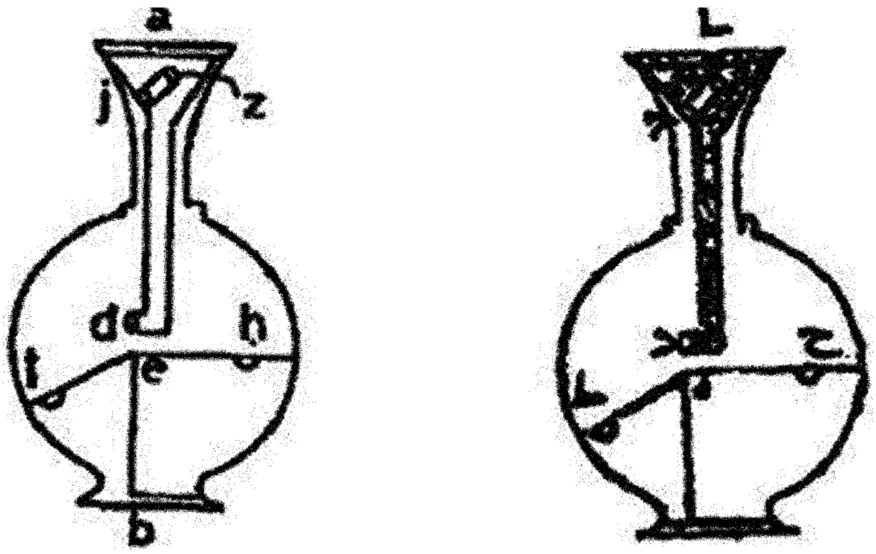

FIGURE 4 (*a*) *Original diagram from Al-Hiyal; and* (*b*) *a modern reconstruction of the two-cache liquid separating jar. See Ghazany, Al-Hiyal* (*cit. note 2*)*, p. 162.*

2 The Two-Cache Liquid Separating Jar

Another example of an innovative design in the book *Al-Hiyal* is "the two-cache liquid separating jar." The shape of the jar resembles that of a laboratory flask with a long neck, as shown in Figure 4a.

This vessel is capable of keeping separate two liquids of different viscosities that are poured into the jar in turn. The liquids are stored inside the jar in two caches and can be poured out again without mixing with one another. When viewed by the observer, two liquids – for example, of different colors – can be poured into the same jar and poured out again separately via the same aperture.

As illustrated in Figure 4a, an upside-down cone (a) is fitted into the neck (j) of the jar so that any liquid poured into it will pass through this cone. From a hole (z) pierced in the side of the cone near its top, a long L-shaped tube extends down into the center of the jar. Liquids poured into the cone will flow down the pipe and exit through the nozzle-shaped end (d) onto either side of the covers – which are inclined at different angles – of two reservoirs concealed inside the jar. The two liquids will flow down one incline or the other depending on their viscosity, and then run into separate caches via hole (t) or (h).

When a viscous liquid is poured into the jar, it will run down the pipe very slowly (due to its cohesion to the sides of the pipe) and for the same reason it will not jet out at any distance from the nozzle-shaped mouth (d). Instead, it will drip straight down onto the inclined top of the reservoir running towards hole (h) and the cache designed to collect the denser liquid. The path followed by the thinner liquids will be different, as they will flow rapidly down the L-shaped pipe and gush out of the pipe's nozzle (d) onto the other inclined surface, running down towards the cache intended for the less viscous liquids and pouring into it via the hole (t). The two liquids will remained stored in these separate reservoirs until the jar is tilted by the user. The direction in which it is tilted will determine which liquid is poured out. When the jar is tilted, the liquid will flow through the side hole (t) or (h) at the top of its cache, into the neck (j) of the jar and then pour out via the side hole (z) of the entrance cone. The same process will take place for the other liquid, but since each leaves the cache via its own aperture, they can be poured out of the jar one at a time without mixing with one another.

This jar may have been used by magicians, although in practical terms it could function for any application requiring the separation of liquids on the basis of their viscosity.

3 The Liquid-Separating Jar with an Inside Cup

This jar also operates on the basis of the viscosities of different liquids. The principle underlying the design of this jar (Fig. 5) is similar to that of the two-cache jar.

As shown in Figure 5a, an upside-down cone (a) is placed at the entrance to the neck of the jar, so that any liquid introduced into the vessel will pass through this cone. The liquid will run downward into a short pipe (j) attached to the narrow end of the cone. The end of this funnel-like device (j) is closed, however, and the liquid will exit through an outlet pipe attached to its side (d).

Here, as in the previous device, due to its viscosity the denser liquid will not gush from the outlet pipe but instead flow slowly down the walls of the cone and drip into the cup (z), from which it can then flow out of the jar again. Thinner liquids will instead pour freely out of (d), splash against the inside wall and flow down into the jar. What the observer will see is one liquid being poured into the jar and then flowing through the outlet (h), whereas a second liquid poured into the jar seems to magically "disappear." This jar, as well as being used to separate liquids, could have been employed by conjurors in their performances.

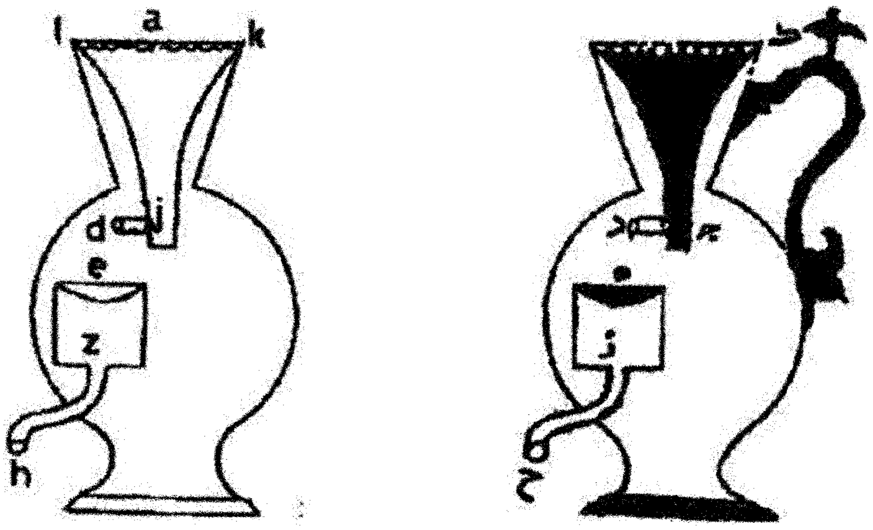

FIGURE 5 (*a*) *Original diagram from Al-Hiyal; and* (*b*) *a modern reconstruction of the liquid-separating jar with an inside cup. See Ghazany, Al-Hiyal* (*cit. note 2*)*, p. 149.*

4 The Liquid-Separating Jar with Two Inside Cups

The design concept of this jar is exactly the same as for the jar with one inside cup, the only difference being that there are two cups, each one of which is connected to a separate outlet pipe. The liquid poured into the jar will flow into one of the two cups based on its viscosity, and then out of the jar through the corresponding outlet pipe. Figure 6 illustrates the jar with two cups for separating liquids on the basis of their viscosities.

As shown in Figure 6a, when a dense liquid is poured into the jar the observer will see it exit through the outlet pipe (z), whereas the thinner liquid will exit through the outlet pipe (w).

5 Results

Four different liquid-separating mechanisms designed by Ahmad ibn Müsä ibn Shäkir Khuräsäni were selected from his book *Al-Hiyal* for study and testing. All of the jars and mechanisms were reproduced in exact accordance with the descriptions presented in the book. Many trials with liquids of different densities and viscosities were carried out and the results obtained using three of the devices were in complete agreement with what is described in the text of *Al-Hiyal*.

FIGURE 6 (*a*) *Original diagram from Al-Hiyal; and* (*b*) *a modern reconstruction of the liquid-separating jar with two inside cups. See Ghazany, Al-Hiyal* (*cit. note 2*)*, p. 151.*

Only the so-called "magic jar" did not seem to work as predicted and therefore modifications to the original design were introduced. These involved slight adjustments to the original set up of the separating mechanism, but the underlying principle of the device remained unchanged. Therefore, the modern experimental set-up for the magic jar constitutes a variation from the design presented in *Al-Hiyal* (Fig. 1b) to the design shown in Figure 3.

6 Conclusion

Four devices for the separation of liquids described in the 9th-century text *Al-Hiyal* by Ahmad ibn Müsa were reconstructed and tested. The three devices which were designed to take advantage of the relative viscosities of different liquids worked exactly as predicted while the fourth and most original device, which exploits the differing densities of liquids, only required a minor modification to its original design set up.

It is well known that the scientific tradition of the ancient world was preserved, continued, and passed on to the West through the studies of medieval Islamic scholars. The lives and work of Ahmad ibn Müsä ibn Shäkir Khuräsäni and his two brothers represent an important example of this activity. The objective of the present project is to document the contribution of Persian scientists to progress in engineering in the early Middle Ages through their own research and inventions, as well as through the conservation and translation of the texts of antiquity.