Guillaume Amontons

Jaime Wisniak.

Department of Chemical Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel 84105.
wisniak@bgumail.bgu.ac.il

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RESUMEN. Guillaume Amontons (1663-1705) fue un experimentador que se dedicó a la mejora de instrumentos usados en física, en particular, el barómetro y el termómetro. Dentro de ellos se destacan, en particular, un barómetro plegable, un barómetro sin cisterna para usos marítimos, y un higrómetro. Experimentó con el termómetro de aire e hizo notar que con dicho aparato el máximo frío sería aquel que reduciría el resorte (presión) del aire a cero, siendo así, el primero que dedujo la presencia de un cero absoluto de temperatura. Durante sus estudios sobre el comportamiento del aire estableció que a volumen constante la presión varía en forma inversa a la temperatura. Desarrolló una máquina de combustión externa y fue uno de los primeros en estudiar el roce en las máquinas (leyes de Amontons-Coulomb).

ABSTRACT. Guillaume Amontons (1663-1705) was an experimentalist who devoted himself to the improvement of instruments employed in physical experiments, particularly the barometer, and the thermometer. Of special note are a folded barometer, a cisternless barometer to be used at sea, and a hygrometer of his invention. He experimented with an air-thermometer and pointed out that the extreme cold of such a thermometer would be that which reduced the spring of the air (pressure) to nothing, thus being the first to recognize that the use of air as a thermometric substance led to the inference of the existence of a zero of temperature. During his studies on the behavior of air he established that at constant volume the pressure varied inversely to the temperature. He devised an external-combustion machine and was among the first to study problems due to friction in machines (Amontons-Coulomb laws).

SOME DETAILS ABOUT LIFE AND CAREER

There are very few details about the life and career of Guillaume Amontons; most of them appear in the obituary published by Bernard le Bouvier de Fontenelle (1657-1757) shortly after Amontons's death.[1]

Guillaume Amontons was born in Paris on August 31, 1663, the son of an advocate who had left his native province of Normandy and established himself at Paris. When Amontons was in the third form (*Troisiéme*) of the Latin school at Paris he became very sick and contracted such a deafness that obliged him to renounce all communications with mankind. Far from regarding this as a handicap, he considered it a blessing, because it allowed him to concentrate on his scientific work without interruption. After unsuccessful labor to build up a perpetual motion machine, he decided, despite his family disagreement, to study physical sciences, celestial mechanics, and mathematics, as well as drawing, surveying, and architecture. So far as is known he did not attend a university. Afterwards, after being employed on various public works projects that gave him a practical knowledge of applied mechanics, he devoted himself to the development, improvement, and design of physical instruments.[2]

Many instruments had been developed to measure in a gross manner the humidity of air. Almost all systems made use of the hygroscopic properties of vegetable or animal fibers such as hemp, oats, leather, or strips of wood. These materials were held by a weight or spring in such a way to displace an index in front of an arbitrary scale as they expanded or contracted [The modern hair hygrometer was invented by Horace Bénédict de Saussure (1740-1799) in 1783].[3] In the year 1687, when he was only twenty-four years old, Amontons presented a new hygroscope of his design to the *Académie des Sciences,* which met with general approbation His apparatus, based on the expansion and contraction of a substance as it absorbs and loses atmospheric moisture, consisted of a ball of beech wood, horn, or leather filled with mercury; it varied in size according to the humidity of the atmosphere.

Between 1688 and 1695 he developed one of the first optical telegraph, which he thought would be of help to deaf people. In his scheme messages were transmitted by means of a bright light that was visible to a person with a telescope at the next station. Although he demonstrated it to the King some time between 1688 and 1695, it was never adopted. As early as 1699 he proposed a thermal motor, a machine using hot air and external combustion with direct rotation. In this work he made his first observations regarding the phenomenon of friction. The experiments carried on in connection with this machine led him also to note that ordinary air going from the temperature of ice to that of boiling water increases its volume by about one third. In the same year Amontons published one of the first known experimental studies on the question of losses caused by friction in machines. The well-known Amonton's laws were in reality a rediscovery of similar facts described by Leonardo da Vinci (1452-1519) years before. Amontons's work included a clear statement of the laws of proportionality between the friction and the mutual pressure of the bodies in contact, as well as an explanation of the causes of friction.

In 1695 Amontons sought to renew the use of the clepsydra (Note 1), operated by the flow of water as a timing apparatus on ships in order to solve the problem of determining longitude at sea. He proposed that his clepsydra could be used at sea, although it would not have been accurate enough to measure longitude.

Between 1702 and 1703 Amontons published some important papers on thermometry, thermometers, and on practical ways of graduating ordinary alcohol thermometers. After observing that the temperature of water remained constant once it achieved its boiling point, he proposed that the latter be used as the fixed thermometric point. He was one of the first to realize the importance of measuring the thermal expansion of elastic fluids. In the absence of an established thermometric scale, and without an accurate thermometer, he could do little more than estimate that air expands, or that its pressure increases by about one-third between the temperatures of cold and of boiling water. He discovered that unequal amounts of air equally heated increased equally in pressure and went on to show that the relative increase in pressure was independent of the initial pressure and dependent only on the rise in temperature, so that if cold air at a pressure of 30 inches of mercury is heated to the boiling temperature of water the pressure increases by about one third, to 40 inches, while air at 60 inches increases to 80 inches, and so forth. He observed that for an equal elevation of temperature the increase of pressure of a gas was always in the same proportion, no matter what the initial pressure. On the basis of the latter finding he proposed an explanation for certain catastrophes, such as earthquakes: If there is air deep within the earth, it is extremely compressed and could reach an irresistible pressure as a result of a relatively small increase in temperature.

Amontons developed the air thermometer, which relied on the increase in volume of a gas with temperature rather than the increase in volume of a liquid. With its aid he found that Newton's law of cooling was seriously inaccurate. Using the air thermometer he devised a method to measure the change in temperature in terms of a proportional change in pressure. He experimented with an air-thermometer, in which the temperature was defined by measuring the length of a column of mercury, and pointed out that the extreme cold of such a thermometer would be that which reduced the "spring" (pressure) of the air to nothing, thus being the first to recognize that the use of air as a thermometric substance led to the inference of the existence of a zero of temperature.[8]

Amonton's dedicated much of his last years to the study of the barometer and built some improved models of the same.[9-13] In 1688 he developed his shortened barometer, composed of several parallel tubes connected alternatively at the top and bottom, with only alternated tubes containing mercury. Another instrument was a barometer with a U-tube, without an open surface of mercury, to be used on shipboard. Using the same receptacle and liquids with different coefficients of expansion, he was able to establish that the theory that "liquids condense and cool first, before expanding with approaching heat" was incorrect because the observed results were actually due to the expansion of the containers. Also, using a barometer as an altimeter, he tried to verify the exactitude of Mariotte's law at low pressures.

In 1695 he published his only book, *Remarques et experiences physiques sur la construction d'une nouvette clepsydre, sur les barometres, les thermometres et les hygrometers*[14] in which he summarized all his work on the development of *instruments*. The book was dedicated to the *Académie des Sciences*.

Amontons was appointed *membre premier titulair*e of the reformed Académie in 1690, after being recommended by the astronomer Jean Le Févre (1652-1706).

According to Fontanelle[1] Amontons lived a very healthy life until the beginning of October 1705 when he had a sudden acute attack of peritonitis; the following infection led to his death on October 11, 1705, at the age of forty-two. His wife and a two-month old daughter survived him.

A two-kilometer diameter moon crater located at the coordinates 5° 18' S/46° 48' O is named after Amontons.

SCIENTIFIC CONTRIBUTIONS

In the course of his comparatively brief career Amontons made a number of important discoveries and put forward some very valuable ideas. His activities as an expert instrument maker led to several fundamental contributions in several areas of physics, which will now be described in detail.

Gases

Bernoulli, in his book *Hydrodyanmica,*[15] refers to Amontons work as follows: "The theorem set out in the preceding paragraph,

Note 1*. The clepsydra was a horological instrument of great antiquity, used by the Egyptians and other eastern nations. It is based on the constant dropping, or running of water through a small aperture, out of one vessel into another. In its simplest form it was a short-necked earthenware globe of known capacity, pierced at the bottom with several small holes, through which the water escaped or stole away. At first the indication of time was effected by marks corresponding to either the diminution of the fluid in the containing vessel, during the time of emptying, or to the increase of the fluid in the receiving vessel during its time of filling; but it was soon found, that the escape of the water was much more rapid out of the containing vessel when it was full, than when it was nearly empty, owing to the difference of pressures at different heights of the surface. The clepsydra, in one of its earlier forms, was used as an astronomical instrument, by the help of which the equator was divided into twelve equal parts, before the mathematical division of a circle was understood; it was deemed of more value than a sun-dial, on account of its dividing the hours of the night as well as of the day. The instrument was employed to set a limit to the speeches in courts of justice, hence the phrases aquam dare, to give the advocate speaking time, and aquam perdere, to waste time.*

namely, that in any air of whatever density, but at a given temperature, the pressure varies as the density, and furthermore, that increases of pressure arising from equal increases of temperature are proportional to the density, this theorem was discovered by experiment by Dr. Amontons… The implications of the theorem is that if, for example, ordinary air at normal temperature can hold a weight of 100 lb distributed over a given surface area, and then its temperature is increases until it can hold 120 lb over the same area and at the same volume, then when the same air is compressed to half its volume and held at the same temperatures, it can support 200 and 240 lb respectively; thus the increases of 20 and 40 lb produced by the increase of temperature are proportional to the density. He asserts, moreover, that air, which he calls temperate, has a pressure approximately 3/4 that of air at the temperature of boiling water, or more exactly, 55/73. But in experiments that I have undertaken I found that the warmest air here at the height of summer, has not the elasticity that Dr. Amontons attributed to "temperate" air; in fact I cannot believe that even at the equator such warm air ever exists (!!)… But I consider that air hot enough to have a pressure equal to 3/4 of that of air at boiling eater temperature would be practically intolerable to a living creature… Accepting this, the temperature of boiling water, of the warmest air in summer, and of the coldest air in winter in this country are as 6: 4: 3. I will now state how I have found these numbers, so that judgment may be passed on the accuracy of my experiments, the outcome of which is quite different from those of Amontons…" There follows a description of the experimental procedure for measuring pressure and temperature. On this basis Bernoulli criticizes the method employed in England for investigating then ratio of the specific gravities of air and mercury, and concludes: "It is clear from this agreement between the conservation of energy in compressed air and in a body falling from a certain height that no especial advantage is to be hoped for from the idea of compressing air when designing machines, and that the principles displayed in the previous parts of this book are valid everywhere. But because it happens in many ways that air can be compressed naturally without applied force, or can acquire abnormal elasticity, there is certainly hope that powerful devices can be invented for operating machines, in the way Dr. Amontons has already described using the energy of fire. I believe that if all the energy, which is latent in a cubic foot of coal and is dawn out of it by burning were usefully expended in operating machines, more could be achieved than by a day's labor by 8 or ten men."

Thermometry

At the time of Amontons no one had yet devised a scale by which temperature could be measured. Between 1695 and 1703 he published several papers[4-7] on his improvements of the air thermoscope that had been invented by Galileo Galilei (1564-1642) in 1593. Galileo's design used the expansion and contraction of the air in a tube to change the level of water, a method that was vitiated by the fact that the water was also affected by changes in air pressure. Amontons remove the effect of pressure was replacing water by mercury and adjusting the height of the latter until the air filled a fixed volume. Changing the temperature of the air in the tube altered the pressure it exerted on the mercury and therefore the instrument should in reality be considered a type of barometer. As a consequence, Amontons's thermometer was more accurate than Galileo's, and he was able to use it to show that, within the limits of his instrument, water always boiled at the same temperature.

In his paper of 1702[4] Amontons described the "state of the art" of thermometry pointing out that thermometers were marked only between the highest and the lowest temperatures observed at a particular region of the earth and that different instruments located in the same place gave different readings. He then asked a very smart question: Assuming that thermometers did not have the limitations he had listed, what was the meaning of one degree of heat in them, what knowledge did this degree provide about the local climate? His answer to this question was very clear: knowledge of the particular degree was of no advantage, at the most it would indicate us that one particular year had been hotter or colder than another one, but not by how much. For this reason he believed that it was necessary to establish a *"certain degré de chaleur constant & invariable, connu de tout le monde, auquel on pût comparer, & qui comprît tous les autres degrés de chaleur qui peuvent être dans l'air que nous respirons"* (it was necessary to establish a certain degree of heat, constant and invariable, known by everyone, on which we could compare all other degrees of heat (temperature) that could be in the air we breathe). For Amontons, this degree of heat necessary for establishing uniformity in the building of thermometers could well be that of boiling water, because experience had taught him that the temperature of water remained constant during its boiling, independently of the intensity of fire. He then proceed to describe a thermometer that he had built that allowed determining the pressure of air that resulted when it was heated by boiling water. The instrument consisted simply of a U-tube having one branch open to the atmosphere and a second much shorter branch ending in a closed tip. The whole U tube was filled with mercury, which sealed the air contained in the bulb. Immersion of the bulb in boiling water gave a clear reading of the (maximum) height of the balancing mercury column. Graduation of the scale downwards provided a scale for indicating degrees of heat below that of boiling water. This scale would be the same everywhere and could be used to compare the temperature at two different locations (it was not known yet that the boiling temperature of water depended on atmospheric pressure).

In this memoir Amontons also gave detailed instructions on how to fill the thermometer with mercury, as well as results of measurements he made during June and July of 1702.

In a following paper[5] Amontons compared the reading of his air thermometer with the old instruments based on wine spirit, which he illustrated as shown in figure 1. Interesting enough, he used a centesimal scale to "quantify" the ancient thermometers from 1 to 100 degrees of heat, corresponding to extreme cold (tres froid) and extreme heat (tres chaud), respectively. This paper was followed by another one[6] converting measurements reported a few months before by Étienne François Geoffroy (1672-1731).

The observant reader will notice immediately that Amontons's air thermometer is actually a thermo-

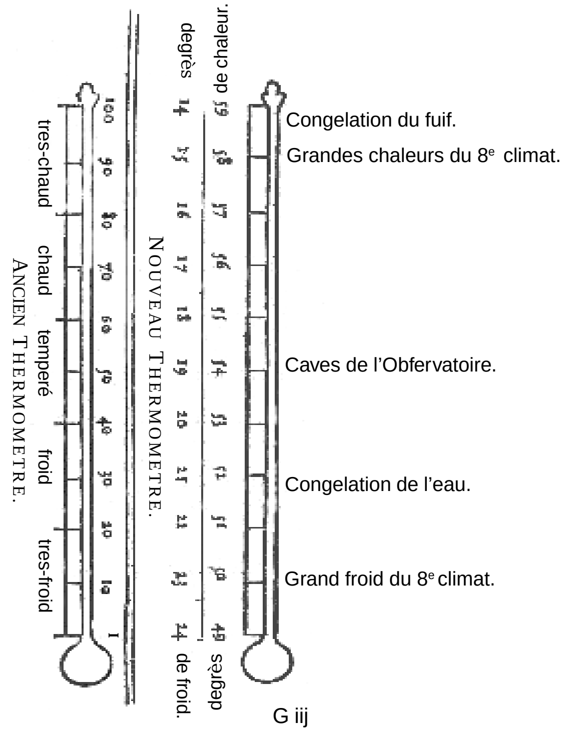

Fig. 1*. Comparison between the readings of a wine spirit thermometer with those of the air thermometer (Amontons, 1703).*

scope, it only allows determining how much hotter or colder is one body with respect to another, but not the actual value of the temperature. Although this limitation prevented him later from discovering Jacques-Alexandre Charles's (1746-1823) law, his new thermometer allowed him to take the study of gases a step further than Edmé Mariotte (1620-1684) had.

Amontons established that if air at atmospheric pressure (30 inches of mercury by his measurements) and at the freezing point of water is held in a constant volume vessel, then if heated to the boiling point of water its the pressure will go up by about 10 inches of mercury. He also discovered that if he compressed the air in the first place, so that it was at a pressure of sixty inches of mercury at the temperature of melting ice, then if he raised its temperature to that of boiling water, at the same time adding mercury to the column to keep the volume of air constant, the pressure increased by 20 inches of mercury. In other words, for a fixed amount of air kept in a container at constant volume, the pressure increased with temperature by about 33 % from freezing to boiling. This percentage was independent of the initial pressure.

More important, Amontons noticed that for a particular change in temperature, the volume occupied by a gas always changed by the same amount. This led to Amontons's law, which he described in 1699 and which can be stated today as $P_1T_2 = P_2T_1$. It also allowed Amontons to visualize a temperature at which gases contracted to a volume beyond which they could contract no further. It was this work that eventually led to the concept of absolute zero in the19th century (see below).

Amontons's air thermometer was bulkier, very fragile, and hard to use, shortcomings that led to its demise.

Absolute zero

Between 1703 and 1704 Amontons published several papers[5-7] where he reported the phenomena he had observed while studying the proper way to calibrate an air thermometer. The greatest climatic cold on the scale of units adopted by Amontons was marked 50 and the greatest summer heat 58, the value of boiling water being 73, and the zero being 51.5 units below the freezing point. He noticed that when the temperature was changed between the boiling point of water and ambient temperature, equal drops in temperature resulted in equal decreases in the pressure of the air. Since degrees in his thermometer were registered by the height of a column of mercury, "which the heat was able to sustain by the spring of the air", it followed that the extreme cold of the thermometer would be that which reduced the air to have no power of spring. In there must be a lowest temperature beyond which air, or any other substance could not be cooled. According to Amontons, this lowest temperature represented a greater cold than what we call "very cold', because his experiments showed that when the "spring of the air" (pressure) at the boiling point of water was 73 inches, the degree of heat which remained in the air when brought to the freezing point of water was still very great, for it could maintain the spring of 5.5 inches. Thus Amontons was the first to recognize that the use of air as a thermometric substance led to the inference of the existence of a zero of temperature. Extrapolation of Amonton's experiments indicated that the air would have no spring left if it were cooled below the freezing point of water, to about 2.5 times the temperature range. On the basis of the 100 degrees difference between the freezing and the boiling points of water the zero of Amonton's air thermometer would be located at –240 °C .

Amontons's brief note presented Johann Heinrich Lambert (1728-1777)[16] with a point of departure for the extension of this idea. Performance of more precise measurements allowed Lambert to fix the absolute zero at –270.30 °C, very close to today's accepted value of –273.15 °C. In order to increase the precision it was necessary to have a better knowledge of the thermal property of gases, which required more information about the general nature of gases. In Amontons's time only air had been studied in certain detail.

Barometer

Amontons made a number of experiments with barometers, proposing several solutions which, however, were never exploited, but which reflect the originality of their inventor, who was well ahead of his time in several fields. His folded barometer of 1688 consisted of a number of parallel tubes connected alternatively at the top and at the bottom; the alternating tubes containing mercury a red liquid. The chief inconvenience of the instrument lay in the reduction of the variation in the level of the mercury.[17]

In 1695 Amontons gave a description of "*un nouveau baromètre très simple et portative à l'usage de la mer*" (a new simple and portable barometer, to be used at sea) that did not have a mercury reservoir.[4] Two types of barometers were described. One consisted, initially, of a tube narrow enough for the mercury column to remain suspended. Amontons gradually broadened the tube into the shape of a slightly conical tube (inverted funnel), closed at the small end and containing a mercury column of suitable length, initially filling the smaller end of the tube. The mercury column would become shorter as atmospheric pressure decreased and longer as it increased. When the tube was inverted so that the closed end was upwards, the column of mercury would fall in the tube until its length (decreasing as its diameter became greater) equalled the barometric height. A scale against which the position of one end of the column was read could give any desired magnification, depending on the rate of change of the diameter of the tube. The lack of reservoir meant that the barometer could be used at sea, where mercury barometers gave unreliable readings because the level of the mercury in the reservoir oscillated with the motion of the ship. Although this was a clear advantage, operation of the instrument was cumbersome: According to Amontons the barometer had to be hung up only when an observation was being made; then it was to be laid flat with great care, or inverted. A drop of mercury frequently separated at the larger end of the column, it could be reunited with the column by the use of an iron wire. In addition, the operation of the instrument was accompanied by a considerable effect of friction. In spite of these shortcomings Amontons considered that his "barometer could serve very well at sea, where the others run too great a risk, for in fact this lack of precision is not considerable enough to prevent the amount by which rains and winds alter the weight of the air being appreciable by this barometer, and we need take no trouble to obtain a greater precision, as it is useless."

The second apparatus described was a combination of a barometer and an air thermometer independent of the atmospheric pressure. Air occupied the top of one of the branches of a U-shaped tube and by its dilation it pushed down one of the mercury columns so that the other end of the branch formed a barometric chamber.

Amontons was puzzled by the friction present in his cisternless in his barometer, because "If we make a simple barometer with a narrow tube, the mercury stays up at precisely the same height as in larger tubes, and the movement of the mercury has the same regularity and precision in each, although the same obstacle which seems to be the cause of the inequality in the one, should also introduce irregularity into the movement of the other." He speculated that the "*la nature cottoneuse de l'air*" (the cotton-like nature of air) was a greater obstacle to the entry of the air into narrow tubes than was the viscosity of the mercury to its motion. It is very possible that the real reason for the friction was dirt present in the mercury and in the glass tube at its open end.

An early attempt to make the barometer portable was made in 1688 by Amontons. He proposed splitting up the height of the mercury column into two or more lengths, with either air or a lighter liquid between them. At the same time the scale could be expanded. A critical and final judgment has been made on this barometer by Daumas:[17] "The barometers of Amontons serve as an example of these short-lived attempts which were so faithfully described in every eighteenth century physics text. The makers produced them regularly to meet the demand of collectors."

An interesting experiment performed by Amontons was related to the height of mercury in a barometer.[12] Now he built the barometer tube from a musket barrel of medium caliber (*34-1/3 pouces de longuer*) welded shut at one end. After it was set up as a barometer tube, the mercury remaining in it could be poured out and weighed. He poured the same amount of mercury in a glass tube and to his surprise the height achieved as different. These results puzzled him because the metal tube was being slowly out gassed, even if the weld was really sound. He concluded that one must assume the atmosphere to be made of particles of air of various sizes (!!), and that iron has large pores than glass (*…autrement qu'en supposant de l'inéqualité dans la grosseur des parties de l'air qui composent l'atmosphere, & des pores plus grands dans le fer que dans le verre.*).

Builders of barometers were aware that the pressure and temperature of the surroundings significantly affected the reading of the instrument. In the beginning they were unable to explain the reasons for this anomaly, which probably included the imperfect vacuum, the presence of water vapor, the expansion of mercury, and the expansion of glass. Originally the expansion of mercury was attributed to the expansion of the air it contained. Amontons was aware that mercury itself expanded or contracted depending on the temperature and tried to determine an empirical correction for the deviation. In a paper published in 1704[9] he reported a comparison on the relative expansion of mercury and wine spirit contained in an apparatus consisting of a large bulb and a calibrated column, at different temperatures, from a "*grand froid to a grand chaud*" (intense cold to intense heat), using the air thermometer he had developed previously. Other scientists did not adopt Amontons's corrections. The measurement of the absolute expansion of mercury with temperature would be resolved almost 110 years later by Pierre-Louis Dulong (1785-1838) and Alexis-Thérèse Petit (1791-1820) in their award-winning memoir.[18]

In order to amplify the changes in reading caused by variations in external pressure Amontons designed and built a barometer containing a column of a red-tinted oil on top of the mercury column.[12] The apparatus consisted basically of two large bulbs connected by a U tube, the top bulb (A) was located at one end, hermetically sealed, and the lower bulb (B) terminated in a long thin tube connected to the atmosphere. The section between the bottom part of bulb A and the lower middle part of bulb B was filled with mercury. The red oil was poured on top of the mercury and its height varied according to the atmospheric pressure.

Telegraph

Communication at a distance is an idea, which has been present in one form of another since people have had any information worth communicating. Early attempts made use of smoke signals, low frequency drumbeats, wind instruments, and as the technology improved, reflecting mirrors, flags, and beacon fires. The information content was low, however, and the satisfactory transmission of information by such visual means developed very slowly in spite of the pressure put by military requirements. Most of the advances were closely connected with continuous development of the optical telescope. The combination of a telescope and a clearly recognizable signaling structure mounted on a hill or tall building and within telescopic sight o a similar structure some distance away, constituted a workable system. On May 21, 1684 Robert Hooke (1635-1703) gave a lecture to the Royal Society, entitled *On Showing a Way How to Communicate One's Mind*, during which he proposed a scheme in which large boards or shutters of different shapes could be hung in a wooden frame to convey by their shape different letters from the alphabet, and viewed from a distance by using a telescope. At each station a telescope would be placed allowing the person stationed at the site to view the communications of the adjacent site.[19]

Hooke's scheme was never put to practice but other inventors took his basic idea further. In 1690, a variant of Hooke's method, developed by Amontons was described in a letter written on November 26, 1695, by Abbé Fénelons, the Archbishop of Cambrai, to Johann Sobieski, the secretary of the Polish King: "Monseigneur has told me that he was in Meudon and from there sent a secret message via windmills to Belleville and from there to Paris. The answer was given to him similarly by signals that were attached to the wings of the windmill and read in Meudon with a telescope. The signals were letters from the alphabet, displayed one after the other, at the rate of the slowly turning mill. As soon as each letter appeared, it was recorded in a table by the observer at the observatory in Meudon. The inventor [Amontons] stated that by increasing the distances, with signals and fire signs one could quickly and cheaply send messages from Paris to Rome; but, I believe, he agreed with me, that this invention is more a curiosity than a practical form of traffic."

Amontons's method is also described in the *Encyclopaedia Britannica*:[20] "Let there be people be placed in several stations, at such distances from each other, that, by the help of a telescope, a man in one station may see a signal made by the next before him; he immediately repeats this signal, which is again repeated through all the intermediate stations, that it may be seen by persons in the station next after him, who are to communicate it to those in the following station, and so on. These signals may be as letters of the alphabet, or as a cipher, understood only by the two persons who are in the distant places, and not by those who make the signals…This, with considerable improvements, has been adopted by the French, and denominated a *telegraphe*; and, from the utility of the invention, we doubt not but it will be soon introduced in this country. *Fas est ab hoste doceri.* [A quote from Ovid, *Met.*, IV. 428, It is right to learn even from an enemy.]

Amontons tried out his optical telegraph in the presence of the Royal family sometime between 1688 and 1695. There is no evidence that anything came of this. Although not adopted in Amontons's lifetime, his ideas were later refined and put into use.

Fire engine

Between 1696-1699 Amontons developed a primitive fire engine that consisted basically of a vertical wheel with hollow spokes and rim, fitted with internal valves. It was partly filled with water, and a fire was lit under one side so that the air in that side of the wheel expanded, and acting through the valves drove the water to the other side. The wheel was thus imbalanced and made to rotate. Amontons actually estimated the duty or the work done for the consumption of a given amount of fluid, that his engine should have yielded, and went on to claim that it compared favorably with the cost of power from the traditional sources: wind, water, and muscle. This approach to the problem of the heat engine was novel, for it showed that Amontons understood that general principles were involved, and also that an idealized engine could be used to compute thermo-mechanical processes.[2]

Evans, in his book about steam engines,[22] gives the following information regarding Amontons's fire engine: "Captain Savary, a gentleman of great ingenuity and ardent mind, saw the reality and practicability of the Marquis of Worcester's project. He knew the great expansive power of steam, and had discovered the inconceivable rapidity with which it is reconverted into water by cold; and he then contrived a machine for raising water, in which both of these properties were employed. He obtained his patent after having actually erected several machines, of which he gave a description in a book entitled *The Miner's Friend*, published in 1696, and in another work published in 1699. We may add, that much about the same time Mr. Amontons contrived a very ingenious but intricate machine, which he called a fire-wheel. It consisted of a number of buckets placed in the circumference of a wheel, and communicating with each other by very intricate circuitous passages. One part of this circumference was exposed to the heat of a furnace, and another to a stream or cistern of cold water. The communications were so disposed, that the steam produced in the buckets on one side of the wheel drove the water into the buckets on the other side, so that one side of the wheel was always much heavier than the other; and it must therefore turn round, and may execute some work. The death of the inventor, and the intricacy of the machine, caused it to be neglected."

Friction

Mankind has used friction between two surfaces in contact since antiquity to produce fire, but understanding of the phenomenon had to wait until the pioneering work of Leonardo da Vinci, Amontons, John Theophilius Desanguliers (1683-1744), Leonard Euler (1707-1783), and Charles-Augustin Coulomb (1736-1806). Their most important findings can be summarized as follows: (1) the force of friction is directly proportional to the applied load (Amontons's first law), (2) the force of friction is independent of the apparent area of contact (Amontons's second law), (3) Kinetic friction is friction is independent of the sliding velocity (Coulomb's law).

The concepts of friction have given birth to the science of tribology (Greek *tribos*: *rubbing*), which concentrates on contact mechanics of moving interfaces that generally involve energy dissipation. Tribology is one of the oldest applied technologies; today it encompasses the science fields of adhesion, friction, lubrication and wear.

Da Vinci can be considered the father of modern tribology; he was one of the first scientists to study friction systematically, particularly for the workings of machines. Among the many related phenomena he investigated are: friction, wear, bearing materials, plain bearings, lubrication systems, gears, screw jacks, and rolling-element bearings.

Da Vinci experiments on friction, done using a horizontal and an inclined plane, led him to conclude that friction is proportional to the normal force and independent on the area of contact. He called the proportional factor "friction constant". Leonardo observed that different materials move with different ease and suggested that this was a result of the roughness of the material in question; thus, smoother materials had smaller frictions. Da Vinci focused on all kinds of friction, he drew a distinction between sliding and rolling friction and concluded that the areas in contact have no effect on friction and that if the load of an object is doubled, its friction will also be doubled. Like with many others of his works da Vinci did not publish his theories on friction, so he never got enough credit for them. The only evidence of their existence is in his vast collection of notebooks. According to Truesdell,[23] da Vinci wrote: "Every body resists in its friction with a power equal to the fourth of its heaviness if the motion is plane (slow) and the surfaces dense and polished (clean)." In modern terms, da Vinci asserts here that the frictional resistance of a sliding body is proportional to the normal force, and assigned to the coefficient of friction the value 1/4. Leonardo did not indicate where he got this figure.

Two centuries after Leonardo's discoveries, Amontons[21] rediscovered the laws of friction while studying the dry sliding of two plane surfaces. In the introduction of his paper he wrote: "The great use which all arts are obliged to make of machines is a convincing proof of their absolute necessity… Indeed among all those who have written on the subject of moving forces, there is probably not a single one who has given sufficient attention to the effect of friction in machines."

Amontons first set of experiments was done using the shown in figure 2. AA and BB are two plates made of different materials (copper, iron, lead, wood, coated with pork fat), of different sizes. The pressure exerted by the spring CCC, maintained at a constant pressure, keeps both plates together. Spring D measures the force necessary for BB sliding over AA.

After testing this arrangement in every possible combination (for example AA made of copper and BB made of iron) Amontons postulated the following friction laws:

(a) *Que la résistance causée par le frottement n'augmente et ne diminuë qu'à proportion des pressions plus o moins grandes suivant que les parties qui frottent ont plus ou moins d'étenduë* (The resistance caused by rubbing only increases or diminishes in proportion to greater or lesser pressure [load] and not according to the greater or lesser extent of the surfaces).

(b) *Que la résistance causée par les frottements est à peu près la même dans le fer, dans le cuivre, dans le plomb, dans le bois, en quelque maniere qu'on les varie, lorsque ces matieres sont enduites de vieux-oingt* (The resistance caused by rubbing is more or less the same for iron, lead, copper and wood in any combination if the surfaces are coated with pork fat).

(c) *Que cette résistance est à peu près égale au tiers de la pression* (The resistance is more or less equal to one-third of the pressure [load]).

(d) *A ces remarques il convient encore ajoûter cettte quatrième, que ces resistances sont entre elles en raison composées des poids ou pressions des parties qui frottent, des tem et des vîtesses de leur movements* (to this remarks it is convenient to add a fourth one, that these resistances are in the composite ratio of the weights or pressures of the rubbing pieces... and the velocity of their movements).

Amontons illustrated his conclusions by saying that if plate AA is pressed over plane BB with a pressure equal to 30 pounds then it takes a force to 10 pounds to move it, independently of the mode of movement. That is, AA could be located on top of a horizontal surface, or hanging from a wheel (pulley). According to Amontons this was a result of the mechanical fact that two forces do not act equally except when they are in the reciprocal ratio of their distance to the supporting point. This is the concept we know today under the name of lever rule.

Amontons believed that friction was predominately the result of the work done to lift one surface over the roughness of the other, or from the deforming or the wearing of the other surface. When two surfaces met the teeth of the upper surface settled into the grooves of the lower surface and to get the upper surface sliding, a lateral force had to lift the teeth out of the grooves (static friction). This caused a loss of energy, which was manifested as a frictional force: "…*nous meditons soigneusement sur la nature du frotement nous trouverons qu'il n'est autre chose que l'action par laquelle un corps qui est pressé contre un autre est mû sur la surface de celui qu'il touché, & que comme les surfaces qui frottent les unes contre les autres ne peuvent être considerées, ou que comme raboteuses & inégales, ou que comme parfaitement units, & qu'il est impossible dans le premier cas que ces inégalités ne soient parties convexes, & parties concaves, & que les premieres entrant dans les dernieres elles ne produisent une certaine résistance lorsqu'on les veut faire mouvoir, puisqu'il faut pour cela qu'elles foûlevent ce qui les presse l'une contre l'aitre...*"

In addition, he explained that that the force to move simultaneously a number of weightless blocks piled one on top of the other and loaded with an arbitrary weight is dependent upon the number of

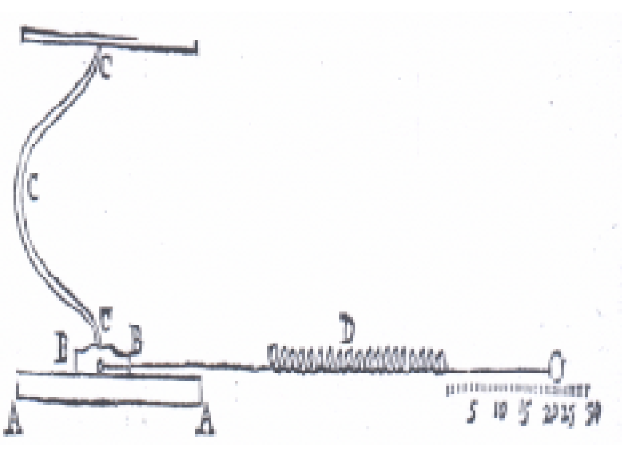

Fig. 2. *Apparatus for measuring friction (Amontons, 1699).*

sliding faces. The resistance at each sliding face is proportional to the weight applied and the total resistance is equal to this force multiplied by the number of sling surfaces.

Amontons then analyzed the friction that takes place between a pulley and a braided cord and prepared a table that allowed a rapid calculation of the force needed to raise a weight as a function of the radius of the pulley, the weight to be lifted, and the number of threads in the cord.

While Leonardo tested static friction Amontons dealt with kinetic friction, although from this writings it is not clear that he was aware of the difference between the two phenomena.

As quoted by Frank Philip Bowden (1903-1968) and David Tabor,[26] the French *Académie des Sciences* received with scepticism the rediscovery of da Vinci's laws by Amontons, which he repeated during the presentation of his fire engine (see above): "*Dans le Discours que fit M. Amontons sur son Moulin à feu, il avança seulement en passant que c'étoit une erreur de croire, comme l'on fait communément, que le frottement de deux corps qui se meuvent en s'appliquant l'une contre l'autre, soit d'autant plus grand, que les surfaces qui frottent sont plus grandes. Il dit qu'il avoit reconnu par experience que le frottement n'augmente que selon que les corps sont presses l'un contre l'autre, & charges d'un plus grand poids. Cette nouveauté causa quelque étonnement à la Académie*".

Euler was the first one to distinguish between static and kinetic friction, because he found that it is not possible to cause a slow motion by slowly increasing the angle of an inclined plan. Coulomb did the most systematic work on friction; he examined the influence of a large number of variables on the phenomenon. Coulomb confirmed Euler's statement experimentally, after measuring kinetic friction at different speeds and finding that friction is independent of the velocity. Coulomb's conclusion that once movement has commenced, the friction force is independent of the velocity, was added as an extension to Amontons's second law. For several centuries after Amontons's work, scientists believed that friction was due to the roughness on the surfaces, and expressed it mathematically as $F \propto \mu L$ where F is the frictional force and L the normal lad that presses the two surfaces together. The coefficient of proportionality, m, or coefficient of friction, depends on the materials and whether the body is at rest or in motion.

The three frictions laws were attributed initially to dry friction only, but it has been well known since ancient times that lubrication modifies the tribological properties significantly (Amontons's experiments themselves were carried using surfaces lubricated by pork fat). However, it was not until the 1880s that Nikolai Pavlovich Petrov (1842-1912) and Osborne Reynolds (1836-1912) studied lubrication experimentally. Both, independently, recognized the hydrodynamic nature of lubrication and introduced a theory of fluid-film lubrication. Analytic results and experiments in ultra-high vacuum have indicated that the static friction between two clean crystalline surfaces should almost always vanish yet macroscopic objects always exhibit static friction. As stated by He *et al.*,[27] there is always some kind of third body present between two surfaces because any surface exposed to ambient air acquires an adsorbed layer of hydrocarbons and other small molecules that is several nanometers thick.

At first look Leonardo and Amontons's laws appear absurd because intuitively one would expect the friction force to be proportional to the area of contact. Bowden and Tabor resolved this paradox in 1939[25] when they distinguished between the real area of contact and the geometric visible area of contact. The real area of contact is only a fraction of the visible area of contact. All experiments lead to the conclusion that friction is proportional to the real area of contact, as intuitively expected.

Adhesion is a term relating to the force required to separate two bodies in contact with each other. In 1734 Desanguliers proposed adhesion as an element in the friction process, a hypothesis that appeared to contradict experiments because of the independence of friction on the contact area (Amontons's second Law). The contradiction between the adhesive issue and Amontons's second law cleared up by the introduction of the concept of the real area of contact. The real area of contact is made up of a large number of small regions of contact, in the literature called asperities or junctions of contact, where atom-to-atom contact takes place. The adhesion concept of friction for dry friction, already proposed by Desanguliers, was applied with great success by Bowden and Tabor to metal-metal interfaces. Bowden and Tabor[25] showed that the force of static friction between two sliding surfaces is strongly dependent on the real area of contact. Their work led to the asperity contact theory of friction. In adhesive wear, asperity junctions plastically deform above a critical shear strength, which depends on the adhesive forces of the two surfaces in contact. Assuming during a frictional sliding process a fully plastic flow situation of all asperities, friction is found to change linearly with the applied load as demanded by Amontons's first law.[27]

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