BENJAMIN THOMSON
Count Rumford

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RESUMEN. Benjamín Thomson, Count Rumford (1752-1814), fue un científico autodidacta, militar, y economista político que vivió y jugó un importante rol durante la turbulenta época de la Revolución Americana y las guerras europeas de los siglos dieciocho y diecinueve. Realizó importantes investigaciones en las áreas de transmisión de calor, medición de la conductividad térmica, fenómenos de superficie, fotosíntesis, óptica, naturaleza de la luz, y alimentación. Descubrió el fenómeno de la convección térmica, demostró que la energía térmica era el resultado de la vibración molecular y que no tenía peso; midió el equivalente térmico de la energía mecánica, desarrollo una potente lámpara para iluminación doméstica e industrial, mejoró en forma substancial el diseño de las chimeneas, disminuyendo su efecto ambiental, así como el mejor uso de los alimentos.

ABSTRACT. Benjamin Thomson, Count Rumford (1752-1814), was a self-educated scientist, military man, and political economist, living during the turbulent period of the American Revolution and the European Wars of the 18th and 19th centuries. He carried on important researches in the areas of heat transmission, measurement of the heat capacity, surface phenomena, photosynthesis, the nature of light, and nutrition. He discovered the phenomenon of thermal convection, proved that thermal energy was the result of molecular vibrations and did not have weight, measured the thermal equivalent of mechanical energy, developed a powerful lamp for domestic and industrial uses, improved substantially the design of chimneys, to decrease their enviromental effect, as well as the better use of food.

INTRODUCCIÓN

Life and career[1-10]

Benjamin Thompson (Fig. 1), afterwards Count Rumford, was born on 26 March 1753 at North Woburn, Massachusetts, the only son of Benjamin Thompson and Ruth Simonds, small village farmers in New England. His father passed away when he was three years old; his mother remarried and reared a large family.[4]

Fig. 1. *Benjamin Thompson, Count Rumford (1752-1814).*

Thompson went to school at Woburn, at Byfield, and then at Medford. After leaving school at the age of thirteen he worked as an apprentice, first to John Appleton, then to Hopestill Capen, storekeepers selling imported dry goods, and then to Dr. Hay. While working for Hay he attended lectures in natural philosophy at the College of Harvard.[7] For some time he worked as a schoolteacher at Wilmington and at Bradford, Massachusetts; in 1772 Coronel Timothy Walker, a local clergyman, invited him to teach in Rumford (now Concord), New Hampshire. Walker's wealthy daughter, Sarah (1739-1792), who had recently become widowed, fell in love with Thompson and within four months they were married. Thompson settled down as a landowner farmer and scientific surveyor of the local country, while cultivating the friendship with John Wentworth (1737-1820), the royal governor of the colony of New Hampshire, an enthusiastic experimenter with agricultural products. In 1773 the governor made him a major in the New Hampshire militia, an appointment that infuriated the professional soldiers of the regiments.[7]

Thomson embraced the Royalist side in the early part of the American War of Independence; his wide knowledge of the local country made him very useful to the British commander in Boston. His behavior and activities arose the suspicions of the settlers and, as a result in 1775 Thompson was summoned to the local committee of safety and accused of being hostile to American freedom. Although the case was dismissed, a menacing mob surrounded his house and forced Thompson to flee to Boston, leaving his wife and only daughter, Sarah, behind. In March 1776 the British army withdrew from Boston and Thompson sailed for England in the frigate bringing the news from General Thomas Gage (1720-1787), the highest-ranking British officer in the Massachusetts Bay colony, to Lord George Germain (1716-1785), the Secretary of State for the Colonies.[7] Germain took Thompson under his care and first appointed him as his private secretary and then to several important offices, among them, secretary for Georgia (1779), Inspector of all clothing sent to America, and Under-secretary for the Colonies (1780). While in London Thompson proposed to recruit a regiment in America for the service of the King; eventually he was sent to New York to carry on this mission, being appointed Lieutenant Commandant of Horse Dragoons of New York, After the signature of peace treaty between England and America (1783) Thompson returned to England, and soon after retired from the army as colonel, with half-pay.[7]

In 1784 Thomson traveled through Europe and at Strasburg befriended the Elector Karl Theodor, king of Bavaria. The Elector took him into his service and appointed him successively his aid-de-camp, his chamberlain, a member of his council of state, and lieutenant-general of his armies. According to Brown[3], Thomson carried on all these positions simultaneously, becoming the powerful functionary in Bavaria, second only to the Elector. Among the many activities he carried on were reorganization of the military establishment, improvement of relations between officers and low rank soldiers and their feeding and clothing, as well as setting garrisons to work growing vegetables for their own use and for the workhouses. He cleared Munich of the beggar plague that affected the city and put them to work making clothing for the army, while providing them with nourishing meals and schoolteachers for their children. Large quantities of soup were made and distributed either by means of tickets, or sold at a very cheap rate. These activities led him to study the science of nutrition and the improvement of fireplaces and stoves, cooking tools (such as stove fuels, pans roasters, pots), etc. etc. He introduced large-scale farming of potato into Bavaria and incorporated it into all of his recommended menus. To feed the maximum number of people with the minimum cost, Rumford experimented with many types of nutritious soups until he arrived at the so-called Rumford Soup, based on barley, peas, and potatoes. He also published a long paper containing many recipes for the preparation of satisfying meals, among them Indian pudding, apple pudding, tagliati macaroni, and potato salad, and encouraged the drinking of coffee as an alternative to alcoholic drinks. Interesting enough, he promoted eating slowly, claiming that this made food more satisfying (a fact recommended today for those wanting to diet). Among the many institutions of public benefit he instituted in Bavaria, is the House of Industry at Manheim, the Military Academy of Munich, and schools of industry for the wives and children of the soldiers, and public gardens. The most famous of the latter is the still existing Munich English Garden.[7]

For these useful services, the King of Bavaria conferred on him several orders of knighthood, paid him lavishly, and in 1793 created him Count Rumford (after the old name of Concord, New Hampshire, in which he was born) and an annual pension of £1,200.[4]

In 1799, after a stay of about twelve years in Bavaria, Rumford returned to England, where he stayed for about two years. In 1802 he went back to Paris and three years later he married Marie Anne Paulze Lavoisier (1758–1836), the wealthy widow of Antoine-Laurent Lavoisier (1743-1794). This marriage was not successful mostly because Rumford's disdain for social life. After the divorce (1809) Rumford move to Auteuil, near Paris, where his daughter joined him in 1811. He died there on 21 August 1814 and was buried in the local cemetery. Countess Rumford, his daughter, returned to America and died in 1852.[7]

In his will he bequeathed the annual sum of one thousand dollars and some of his properties to Harvard University to establish a chair to teach "the utility of the physical and mathematical sciences, for the improvement of the useful arts, and for the extension of the industry, prosperity, happiness, and well-being of society." He suggested the establishment, and brought to reality, the Royal Institution of Great Britain.[11] In 1796 he founded two prizes, to be annually awarded by the Royal Society of London and the Philosophical Society of Philadelphia (American Academy of Arts and Sciences of Boston), to the author of the most important experiments on heat and light.[4]

Rumford received many honors and awards for his scientific and public activities. He was Count Rumford of the Holy Roman Empire and the King of Poland decorated him with the Order of Saint Stanislaus of Poland, with rank White Eagle. He was an honorary member of the Royal Society and of the Royal College of Physicians of Edinburgh, a member of the Academies of Munich, Manheim, Berlin, the Royal Irish Academy, the Irish Society for the Encouragement of Arts, the American Philosophical Society of Philadelphia, the American Academy of Arts and Sciences in Boston, and one of the eight Foreign Associates of the Institut de France. He received a gold snuffbox as a tribute for this support in restructuring the culinary establishment of Heriot's Hospital.

Rumford's scientific curiosity, acute observation mind, and numerous military, public, and political activities led him to carry on research in a wide variety of subjects. For example, from the manufacture of weapons, particularly cannons, came papers about gunpowder, its force and measurement, including an improvement of Robin's procedure [1]; the conversion of mechanical work into heat; experimental evidence against the phlogiston theory, and the proof that heat was transferred by molecular vibration.[12-16] The need to improve the lighting conditions in dwellings and public buildings led to his studies on the properties, nature, and measurement of light, and the design of an improved lamp.[17-21] Observation of natural phenomena and the welfare of soldiers, drove him to examine the mode of heat transfer in different media and its consequences upon climate; to the design of an apparatus for measuring thermal phenomena, the study of combustion phenomena and the design of improved stoves and chimneys.[22-37] Others significant contributions were related to photosynthesis,[38] humidity,[39] and surface phenomena.[40]

SCIENTIFIC CONTRIBUTION

Thomson published more than 80 papers on a variety of subjects in physics, chemistry, thermodynamics, and climate. A few of them are described below.

Light phenomena

Photosynthesis

Jean Ingenhousz (1730-1799) had discovered that the leaves of plants living under water gave of oxygen when exposed to the rays of sun,[41] and Joseph Priestley (1733-1804) had observed that when water became green it always yielded more of this gas than common water.[42] These experiments had led to the theory that vegetables decompose water, retaining the hydrogen and giving out the oxygen, and that by this process the oxygen taken from common air by animals and combustion was restored. In his paper about the production of dephlogisticated air (oxygen) from water[38,43] Rumford wrote that since he was not completely satisfied about the explanations provided for the results of Ingenhousz, he had decided to conduct some experiments to elucidate the causes. He begun by mentioning his previous findings that raw silk exposed to the action of light "possessed the power of attracting and separating air from water in great abundance"[39], and that it appeared to him of interest to examine the properties of the air released. He remarked that the purpose of this work was to report results, without applying them to the confirmation or refutation of the results obtained by other scientists. Thus, in speaking of the air produced upon exposing raw silk in water to light, he would sometimes mention it as being yielded by the silk, and other times, as furnished immediately by exposing water, which previously had turned green (decomposed); though it was probable that in both cases the *green matter* played a very important part in the production of this.[38]

In Ingenhousz's procedure, plants were grown inside inverted glass globes full of water and the released gas collected and analyzed for its oxygen content. Rumford's initial experiments followed Ingenhousz's technique to collect a sufficient quantity of the air separated from water by silk to determine its quality by testing it with nitrous air (nitrous oxide). He promptly found that this setup made it very difficult to compare the volumes of gas released. He therefore modified it so that the gas displaced water, which could be easily collected as an overflow and therefore continuously measured during the advancement of the experiment. For this purpose, he filled a transparent glass globe with clear spring water and then introduced into it a certain amount of raw silk, which had been previously washed in water in order to free it from air. The globe was then inverted and put under water in a glass jar containing water of the same source, and exposed it to the action of sunlight. He collected all the gas released during a period of four days. The gas obtained was separated and mixed in 1:3 volume ratio with nitrous air (nitrous oxide), prepared by reacting fine copper wire in smoking spirits of nitre (KNO_3), and then diluted in water. The substantial reduction in volume that took place proved that this air was actually very pure *dephlogisticated air*. Introduction of a small wax taper in the gas inflamed it immediately, with a very bright and enlarged flame. The water remaining in the flask lost part of its transparency and changed its color to a very faint green. Rumford also indicated that when the sunlight was very bright, the quantity of air released was not only larger but also of superior quality. The same experiments conducted in the dark did not produce any measurable quantity of gas.[38]

Rumford then carried out 27 experiments under different conditions, for example, in total darkness, total darkness and heat, exposition to light and with the globe immersed in an ice and water mixture, the action of artificial light instead of sunlight, using other materials (wool, fine fur, cotton, human hair, and linen), submerging fresh healthy vegetables in water, changing the number of days exposed to sunlight, amount of silk added to a given amount of water, etc. etc.

Microscopic examination of the resulting water in an experiment done with poplar cotton showed the presence of a large number of animalcules (microscopic aquatic microorganisms), exceedingly small and of nearly a round figure. Rumford remarked that he had had been unable to understand the part these animalcules played in the operation of purifying the air in water. He stated that Priestley had found that many animal and vegetable substances putrefying or rather dissolving in water, in the sun, caused the water to yield large quantities of dephlogisticated air. Rumford believed that the silk and other materials he had employed did not participate (considered as chemical substances) in the process pure air production by water. They merely acted as mechanical aids in *separating* the air from the water by providing a suitable surface for the air to attach itself to. To prove this point, he performed additional experiments in which he substituted the silk by fine flexible threads of glass (used for producing brushes and artificial feather). The results confirmed his thoughts: a large amount of air was released on exposure to sunlight.[38]

In a postscript to his paper, Rumford wrote that that his experiments proved that the dephlogisticated air produced by exposing fresh vegetables in water to the action of sunrays resulted from the removal of the air contained in the water, contrary to the generally accepted opinion (Ingenhousz's) that it was *elaborated* in the vessels of the plant. In his own words, "that the fresh leaves of certain vegetables exposed in water to the action of sunrays, cause a certain quantity of pure air to be produced, is a fact which has been put beyond all doubt, but it does not appear to me to be by any means so clearly proved, that this air is *elaborated* in the plant by the "powers of vegetation"…phlogisticated or fixed air (nitrogen) being first absorbed or imbibed by the plant as food, and the dephlogisticated air (oxygen) being rejected as an excrement, for besides that many other substances…in which no elaboration…can possibly be suspected to take place, cause the water…to yield dephlogisticated air as well as plants…" As a further argument he indicated that experiments done by others (mainly Ingenhousz and Priestley) had indicated that fresh healthy leaves of vegetable, separated from the plant, and exposed to the action of sunlight, appeared to furnish air only for a short time; after a day or two the leaves changed color and ceased to yield air. The latter result was conceived to arise from a destruction of the power of vegetation (the death of the plant). He then described the results of four additional experiments that confirmed that the leaves ceased to furnish air, yet, after a certain time they *regained* this power and furnished more and better air than at first.[38]

Rumford concluded his paper suggesting that the manifestations he had described could be accounted for by "assuming that the air produced in the different experiments had been generated in the mass of water by the *green matter*, and the leaves, the silk, etc; did no more than *assist in making its escape* by affording a convenient surface to which it could attach itself…[or] by supposing the *green matter* to be a vegetable substance, agreeable to the hypothesis of Priestley, that attaching itself to the surfaces of the bodies exposed in the water it grows…exerting its vegetative powers…and produced the air.'' He rejected the second possibility because microscopic examination at the time when there was an abundant release of air, showed that the absence of anything that could be considered to be of vegetable nature. The "coloring of the water was a result of the assemblage of a large number of animalcules, without anything resembling *tremella* or that kind of *green matter*, or water moss, which forms upon the bottom and sides of standing water".[38]

His paper ended with the following comments: "Perhaps all the appearances above described might be satisfactorily accounted for, by supposing the air produced in the different experiments to have been generated in the mass of water by the green matter; and that the leaves, the silk, etc., did no more than assist it in making its escape, by affording it a convenient surface to which it could attach itself, in order to its collecting itself together, and taking upon itself its elastic form. The phenomena might likewise be accounted for by supposing the green matter to be a vegetable substance, agreeable to the hypothesis of Dr. Priestley, and that attaching itself to the surfaces of the bodies exposed in the water, as a plant is attached to its soil, it grows; and, in consequence of the exertion of its vegetative powers, the air yielded in the experiment is produced. I should most readily have adopted this opinion, had not a most careful and attentive examination of the green water, under a most excellent microscope, at the time when it appeared to be most disposed to yield pure air in abundance, convinced me, that, at that period, it contains nothing that can possibly be supposed to be of a vegetable nature. The colouring matter of the water is evidently of an animal nature, being nothing more than the assemblage of an infinite number of very small, active, oval-formed animalcules, without anything resembling *tremella* (a parasitic fungi), or that kind of green matter, or water moss, which forms upon the bottom and sides of the vessel when this water is suffered to remain in it for a considerable time, and into which Dr. Ingenhousz supposes the animalcules above-mentioned to be actually transformed".[38,43]

His paper drew considerable criticism; two years later Jean Sennebier (1742-1809) repeated Rumford's entire set of experiments and concluded that they were mistaken wrong and that "it was probably the air contained in the water which separated in the Count's experiments".[44,45]

Light intensity and measurement

In a paper published in 1794,[19] Rumford described his experiments comparing the intensity of the light of a clear day with that of a common wax candle. He let the light from the north to fall at an angle of about 70 ^{0} upon a sheet of white paper, and also the light of candle in such a position that its ray fell upon the paper in the line of reflection of the daylight. He then put a cylinder of wood about one-half inch diameter at about 5 cm from the surface and was quite surprised to find that the two shadows projected by the cylinder on the paper instead of being colorless, the one corresponding to the beam of daylight was blue and that to the candle was yellow. Approaching the candle to the paper made the blue shadow deeper blue and the yellow fainter. Removing it far away caused the opposite effect, the blue became fainter and the yellow deeper. Rumford believed he understood why the shadow of the candle was yellow but not why the shadow from the sky was blue, particularly after repeating the experiments with skylight reflected from a roof covered by white snow, or using two candles and interfering the light of one with a pane of yellow glass. Once again one of the shadows was yellow and the other blue.[19]

Another unexpected result occurred when interposing a sheet of yellow or orange glass on the path of the candlelight. This time its shadow became orange while the blue shadow remained unchanged and the whole surface of the paper appeared tinged violet, approaching pink. These unforeseen results led Rumford to suspect that the colors of the shadows were simply an optical deception, owing to contrast, or some effect of the other neighboring colors upon the eye. Consequently, he performed a series of additional experiments changing the source of the light, its angle of incidence upon the paper, using two lamps instead of daylight and candle, or a flat ruler instead of a cylinder, looking with one eye at the shadows through a tube lined with black paper, etc. etc. Far from being able to observe any change in the shadow upon which his eye was fixed, he was unable to tell when the yellow glass was before the lamp, and when it was not, and could not discover in it the least appearance of any color at all. But as soon as he removed his eye from the tube and looked at the shadow with all its neighboring accompaniments, the original yellow and blue colors reappeared.[19]

Rumford concluded his paper stating his belief that "additional experiments may lead not only to a knowledge of the real nature of the harmony of colors…but also enable us to construct instruments for producing that harmony for the entertainment of the eyes in a manner similar to that in which the ears are entertained by musical sounds".[19]

As a result of his work on the intensity of light, Rumford believed he had found a very simple and accurate method or measuring the relative quantities of light emitted by lamps of different constructions, candles, etc. etc. His procedure consisted in putting in a dark room two burning candles, lamps or other lights, separated one from the other by about 2 meters, and located at equal heights from the floor. The lamps shone on a piece of paper located at a distance of about 2 meters, in such a manner that a line drawn from the center of the paper, perpendicular to its surface, would bisect the angle formed by the lines drawn from the lights to that center. In this arrangement one light would be precisely in the line of reflection of the other. A small cylinder of wood, about ¼ in diameter and 6 inches long, was held in a vertical position at about 5 to 7 cm from the center of the paper and in such a manner that the two shadows of the cylinder corresponding to the two lights could be noticeably seen upon de the paper. One of the two lights was now moved (away or closer to the paper) until both shadows seemed to have the same density. In this situation the ratio of the real intensities of the two lights was be found to be equal to the ratio of the square of their distances to the center of the paper. Rumford named this apparatus *photometer* and afterwards modified its construction in order to reduce the errors to a minimum.[18] He also used it made a series of additional experiments to determine the resistance of the air to light, the loss of light in its passage through plates or panels of different kinds of glass, the loss of light on its reflection from the surface of a plane glass mirror, the relative quantities of oil consumed and the light emitted by an Argand's lamp [2], the relative quantities of beeswax, tallow, olive oil, rape oil, and linseed oil, consumed in the production of light, the transparency of flames, etc. etc. His results indicated that the flame was always perfectly transparent and permeable to the light of any another flame; that the quantity of light was not proportional to that of the heat, and that it did not depend, like the latter, upon he quantity of matter burnt, but rather upon the strength of the composition.[4,18]

Nature of light

According to Rumford those who considered light as a substance emitted by luminous bodies, had been obliged to search for the source of that which was manifested in the combustion of inflammable bodies among those substances, which were known to concur in that process.[35] "Some had supposed that it was the inflammable substance which furnished it, others, that it was derived from the air (oxygen gas) employed in the combustion, which was supposed to be decomposed, and a later opinion appeared to be that it was furnished in part by the inflammable substance and in part by the oxygen". Rumford commented that "if the light manifested in the combustion of inflammable bodies were in fact on of the chemical products of that process, as had been supposed, it was most certain that it ought to be found *pre-existing* in some of the bodies which were decomposed in that operation, and there was every reason to suppose that if that were really the case, that the quantity of light disengaged in the combustion of a given quantity of any given inflammable substance would be limited, and just as invariable as all the other chemical products of that process. But if the light was not a substance emitted by luminous bodies but a vibration and undulation in an ethereal fluid, analogous the vibration and undulation of the air, which is the immediate cause of sound. In this latter case, it was necessary to search for the cause of light, which was diffused by the flame of a burning body in the very high temperature of the particles of matter, which composed the flame. These particles must be considered as being luminous, in consequence of the action of the same cause, which rendered a cannon bullet luminous, which had been heated, red-hot in the fire. Since all known bodies ceased to shine in the dark at a given temperature, the hot particles which composed a visible flame ought to disappear completely ought to disappear entirely the moment they became cooled down to that temperature. Assuming this hypothesis to be true, we must no longer expect to find the quantities of light excited in the process of combustion to be in any constant ratio to the quantities of inflammable substance burned".[35]

In order to clarify this question, Rumford carried on a series of experiments to measure the intensity of light. Before doing so he improved the performance characteristics of his photometer. Among other things, he chose as standard light a wax candle of the first quality, 0.8 inches in diameter, burning with a clear and steady flame and consuming regularly 108 grains Troy of wax per hour. To this standard he assigned the value 100 ^{0}. He then reported the intensity of the light produced by an Argand lamp under different conditions and found that the quantities of light furnished were very far from being in a constant ratio to the quantity of oil consumed. After a series of experiments with other sources of light, for example, beeswax candles, Rumford remarked that "as long as the doctrine which supposes light to be a substance emitted by luminous bodies continues to be believed and universally taught, a great number deal of time will no doubt continue to be employed in *useless researches* concerning its supposed affinities and combinations".[35]

An interesting by-product of these researches was Rumford's development of a modification of the Argand lamp, able to generate substantial more light than the original model. In it, the single burning ribbon was replaced by four wicks, each 1.6 in wide, placed vertically, one by the side of the other, at a distance of about 0.2 in, and so separated as to let the air come between them. This arrangement gave more light than six standard Argand lamps burning with their usual brilliancy. Some of these new lamps were found to give 5200 ^{0} of light, equivalent to that of 52 wax candles of the best kind.[21,35]

Chemical properties of light

Rumford had previously mentioned that he did not believe that light had chemical properties and that the visible changes produced in bodies by exposure to the action of the sunrays were not affected by a chemical combination of the matter of light with the bodies, but simply by the heat generated or excited by the light they absorbed.[19] Finding that gold or silver could be melted by the heat (invisible to the sight) present in the air at the distance of more than 3 cm above the point of the flame of a wax candle,[17] he was curious to know what effect this heat would produce on the oxides of those metals. He now conducted eight experiments in which he exposed a piece of white taffeta ribbon wet with solutions of the oxides of gold, silver, or magnesium, to the action of the flame of a burning candle, or the direct action of sunlight. For example, in the first experiment, he dissolved gold in aqua regia, evaporated to dryness the solution, and dissolved the residue in enough distilled water to avoid crystallization. He moistened a taffeta ribbon with the solution and held it over the clear bright flame of a wax candle. In a few seconds the wet spot turned purple and became indelible. Treatment with super oxygenated hydrogen chloride increased the intensity of the purple color, approaching it to reddish brown. Rumford was unable to find traces of gold. The same results were obtained when the ribbon was first dried in the dark, when the ribbon was made of paper, linen, or cotton, and also when using a solution of silver nitrate. In the latter case the spot was colored dark orange instead of purple. Rumford also reported that the heat released from the flame was enough to melt a very fine silver wire.[17]

In another experiment he moistened fine impalpable magnesia alba with the aqueous solution of gold oxide and exposed one half of it to sunlight, while keeping the other half in darkness. The magnesia exposed to sunlight begun almost immediately to change color, first becoming violet, and then, after a few hours, turned into deep purple. The portion kept in the dark retained the yellowish hue it had acquired from the solution, without the smallest appearance of change. When the wet magnesia alba was let to dry and then exposed to the sunrays, it acquired a faint violet hue, which turned deep purple if wetted again.[17]

The result of all these experiments led Rumford to conclude that light had little effect in changing the color of metallic oxides, as long as they were in a state of crystallization. The heat that was generated by the absorption of light had necessarily, at the moment of its generation, "exist in almost infinitely small spaces" and consequently, it was only in "bodies that are infinitesimal small" that it could produce durable effects. "The easiness, with which the metallic oxides could be reduced, by the *dry via*, by means of charcoal, showed that at a certain (high) temperature, oxygen was disposed to quit those metals in order to combine with the charcoal". Hence, Rumford thought that gold might be rejuvenated by the *wet via*, by means of charcoal and sunrays; to test this point he performed an additional series of eight experiments in which he added small pieces of charcoal to the solution of gold in aqua regia, and exposed the mixture to the action of sunlight. Within a few hours the solution, originally bright yellow, became colorless and small specks of gold begun to appear on the surface of the charcoal and the inside of the tube. The same results were obtained with a diluted solutions of the oxide of gold, while holding the solution in the dark and heating to 210 ^{0}F; with a solution of silver nitrate mixed with charcoal and exposed to sunlight or kept in the dark and heated to 210 ^{0}F; and with solutions of gold oxide in sulfuric ether (ethyl ether).[17]

Heat phenomena

Conductivity

In 1786 Rumford observed that vacuum was a worse conductor of heat than atmospheric air and measured the relative conductivity or water and mercury under different circumstances.[22] In a following paper[23] he reported the relative thermal conductivity of fluids and solids of different nature, particularly of substances commonly used for clothing (i.e. raw silk, sheep wool, cotton wool, linen, fur of beaver, fur of a white Russian hare, and elder down) His experimental procedure was very simple. A thin mercury thermometer was introduced down to the center of a glass globe and the intermediate volume filled with 16 g of the material whose conducting power was to be determined. The whole apparatus was first submerged in boiling water and then in a freezing mixture of crushed ice and water, while the times of cooling were noted down. Since the interstitial space was always full with air, Rumford employed his apparatus to measure the conductivity of air, and used it as the comparison standard. For every substance he registered the time required to cool it from 700 to 100 ^{0} Réaumur (87.5 ^{0} to 12.5 ^{0}C). The total times for this temperature interval were 576, 1032, 1046, 1118, 1284, 1296, 1305, and 1315 seconds for air, fine linen, cotton wool, sheep wool, raw silk, beaver fur, elder down, and hare fur, respectively. Since the conductive powers were inversely proportional to these times, these results meant that the warmest substances were hare fur and elder down. The next set of experiments was carried on to determine the effect of the density of the material on the conducting power. For example, changing the weight of elder down loaded in the apparatus from 16 to 30 and to 60 grams, resulted in an increase in the cooling time from 1304 to 1472 and 1615 seconds, respectively. He also investigated the relative conductivities of the solid material and the air that occupied the interstices of the substance. His results indicated that this air played an important part in the act of confining heat (insulating power). Although individual particles of air were able of receiving and transporting heat, quiet air was unable of doing so, that is, in the latter state air was essentially a non-conducting material. In addition, there was a strong attraction between the particles of air and the fine hair or furs of animals, bird feathers, etc. These substances retained the air adhered to them even when immersed in water and subject to the action of a vacuum pump. These results explained why the finest, longest, and thickest furs, were the warmer.[23]

Convection

Rumford's discovery of the existence of convection currents in fluids was also accidental.[24,46] During a set of experiments on heat phenomena he used liquid thermometers having large diameter bulbs (10 cm). One of them, containing alcohol, happened to be placed in a window exposed to the sun. When looking at it "he saw the whole mass of its contents in a most rapid motion, in two opposite directions, up and down at the same time. These motions were rendered visible by some particles of fine dust that happened to be in the ball before it was filled. The tube was 43/100 inch in diameter, and upon examination with a lens, the rising current of spirit was seen to occupy the axis…of the tube, and the descending stream was contiguous to the sides. When the tube was inclined, the rising current occupied the uppermost side and the descending stream the lower. The velocities were perceptibly increased by wetting the tube with ice water; they became gradually less as the thermometer was cooled, and ceased then the fluid had acquired the temperature of the room, and the motion was greatly prolonged when the cooling of the bulb was impeded by wrapping it in furs or any other warm covering The same experiments, with motion of the same kind, as quite as rapid, were repeated with a similar thermometer filled with linseed oil".[24]

Rumford concluded that heat transfer was transferred in fluids "only by its being transported by virtue of their intestine motion produced by the change in specific gravity…and that there may be two ways of obstructing this propagation of heat, namely by diminution of their fluidity, which may be done by solution of any mucilaginous substance, or more simply, by impeding the motion of their particles…by mixing any solid substance…which is an imperfect conductor of heat and of an enlarged surface by being divided into small masses".[24]

The rate of heat transfer was reduced when increasing amount of a light substance were mixed with a liquid (water) or a gas (air). Thus feathers or hair would produce the same effects in water as in air, feathers or hair would produce the same effects in water as in air. Rumford concluded his paper with the comment that his findings about the poor conductivity of heat by water "could be used to explain the great operations (climate), which were regulated and performed on the surface of the globe".[24]

In a paper about the mode of propagation of heat in liquids[30] Rumford wrote that "when heat was propagated in solid bodies, it passed from particle to particle and apparently with the same velocity in every direction", but his was not the manner in which it propagated through liquids. When a hot solid body was plunged in a cold liquid, the particles of the liquid in contact with the solid became lighter than the surrounding particles and rose to the surface of the liquid; the cold particles that replaced them at the surface of the hot body, repeated the same process. "All the particles thus heated by a successive contact with the hot body formed a continuous ascending current which carried the whole of the heat immediately towards the surface of the liquid, so that the strata of the liquid situated at a small distance *under* the hot body were not sensibly heated by it. In the same manner, when a solid body was plunged in a liquid hotter than the body, the particles of the liquid in contact with the body descended as a result of the increase of their specific gravity, and fell to the bottom of the liquid, and the strata situated *above* the level of the old body were not cooled by it immediately". To this facts Rumford added the comment that although the viscosity of the liquids was still to great to allow to allow one of their particles individually being moved out of its place by any change of specific gravity occasioned by heat or cold, this did not prevent currents from being formed in the manner above described.[30]

Heat equivalent of work

While Rumford was working in the boring of cannon in the workshops of the military arsenal at Munich, he was struck by the considerable temperature achieved by a brass cannon within a short time in being bored, and with the extreme temperature (much higher than that of boiling water) attained by the metallic chips separated from it by the borer.[15] He thought that investigation of these phenomena would allow him to get a better understanding of the true nature of heat as well as provide some reasonable assumptions regarding the existence or non-existence of an *igneous fluid*. Some of the questions to be answered were (a) what is the origin of the heat produced in the mechanical operation of boring? (b) Is it furnished by the metallic chops, which were separated? If this was the case, then the caloric theory predicted that the heat capacity of the metallic chips should have changed sufficiently to account for *all* the heat produced. This assumption was promptly rejected when he found that equal weights of thin slips of the block of metal and of the chips, initially at the temperature of boiling water and then put into equal quantities of cold water (59 ^{0}F), achieved the same final temperature; proving that the heat was generated from a different source.[15]

Rumford determined the amount of heat generated by the mechanical borer by measuring the time necessary for this heat to boil a given quantity of water. For example, he found that the heat generated by the friction of a steel borer against gun metal, pressed against it with a force of about 10,000 lb and turning at about 32 rpm, was enough to boil 8.5 kg of water in two hours and a half. This amount of heat was equivalent to the heat generated by nine large wax candles (each one 3/4 in diameter and weighing 15.9 g), burning continuously with a clear flame. Rumford took extreme care to reduce as much as possible the loss of part of the heat generated in the experiment. For this reason, he covered the cylinder with a thick layer of warm flannel and protected it on every side from the cold air of the atmosphere. Rumford's results clearly indicated that the heat generated in the process of boring cannon was a definite, measurable quantity, which did not reduce as long as the experiment was continued.[2] In his words: "as the machinery used in this experiment could be easily carried round by one horse, his computations showed…how large a quantity of heat might be produced by proper mechanical contrivance, merely by the strength of a horse, without either fire, light, combustion, or chemical decomposition…In reasoning on this subject, we must not forget to consider…that the source of the heat generated by friction in these experiments, appeared evidently to be *inexhaustible*. It is hardly necessary to add that anything which any insulated body or system of bodies, can continue to furnish *without limitation*, cannot possible be a *material substance*, and it appears to me extremely difficult…to form any distinct idea of anything, capable of being excited and communicated in these experiments, except it be MOTION".[15]

Weight of heat

In a following paper Rumford addressed in more detail the question about the weight, gained or lost, when heating a body. The pertinent measurements were of a very delicate nature and liable to many errors caused of the imperfections of the instruments used, and from the vertical currents in the atmosphere caused by the hot or the cold body, which was being weighed. Hence, it was not surprising that there were so many conflicting opinions about the issue.[16]

Rumford carried on many experiments on the subject taking all the precautions to avoid errors. All his results convinced him more and more that a body acquired no additional weight upon being heated, or rather, that heat had no effect whatsoever upon the weight of bodies. Sometime before, George Fordyce (1736-1802) had reported that his experiments proved that bodies became heavier the more they were cooled, so that heat resulted in a diminution of weight.[47] Hence Rumford decided to repeat them to "convince myself whether the very extraordinary fact related might be depended on", taking advantage that he had access to an excellent balance owned by the Elector Palatine Duke of Bavaria.[16] For his first experiments, he took two Florentine flasks, built of very thin glass, and filled one with pure distilled water and the other with the same weight of diluted spirit of wine (alcohol). The flasks were closed hermetically, wiped clean and dried on the outside, hanged from the arms of the balance, and then the whole arrangement placed in a large room which had been previously warmed for four weeks with a stove to about 61 ^{0}F. After verifying that the flasks remained counterbalanced, Rumford transferred the arrangement to another large room in which the air was very quiet and at 29 ^{0}F, and left it there for forty-eight hours. He was surprised to find that the flask containing the water (which had frozen) weighed more than the one with the alcohol (which remained liquid). He returned the balance and the flasks to the original room, which was still at 61 ^{0}F, let the water return to the liquid state, and after wiping both flasks clean and dry on the outside, he was again surprised to find that the two flasks had once more the same weight. These surprises led him to verify his experimental procedure. He first made sure that the balance was working correctly and that the difference in weight was not caused by a difference in the texture of the arms by suspending from the two arms two brass flasks filled with the same amount of mercury (since he knew that metals did not attract moisture). He also took extreme care to avoid any influence of external currents of air originating from the difference in density caused by the change in temperature between the two rooms (61 ^{0} and 29 ^{0}F). The following experiment consisted in filling one flask with a given weight of water and the other, with the same weight of mercury. Repeating the previous experimental procedure, he found that this time both flasks had the same weight. In this situation, it was clear that the quantity of heat lost by the water was considerably greater than the one lost by the mercury; nevertheless, it did not reflect in a change in weight of the two fluids. These results convinced him that the original outcome arose from an accidental cause, most probably a lack of thermal equilibrium between the flasks, which also led to a greater or less quantity of moisture to remain attached to each one. After leaving the flasks to remain at each temperature level for a considerable time he was happy to see that he had found the correct explanation: this time both flasks remained all the time in exact counterpoise. Rumford indicated that the hypothesis of many scientists that "heat was nothing more than an intestine vibratory motion of the constituent parts of heated bodies," made it clear that the weight of bodies could not be affected by such motion".[16]

Rumford ended his memoir with the following quantitative remarks: Water upon freezing had lost a quantity of heat amounting to 140 ^{0}F. If this amount of heat was absorbed and retained by an equal quantity of water, it would raise its temperature to (32 + 140) = 172 ^{0}F, short by 40 ^{0}F of that of boiling water. The capacity of water to receive and retain heat was known to be to that of gold in the ratio 20:1; consequently, if the heat lost by freezing a given quantity of water was communicated to an equal quantity of gold, the latter instead of being heated to 172 ^{0}F would be heated to (140) (20) = 2800 ^{0}F, that is, it would be raised to bright red heat. Now, if the weight of old is neither augmented or diminished by one millionth part…we may safely conclude that all attempts to discover any effect of heat upon the apparent weights of bodies will be fruitless".[16]

Heating with steam

In 1745 Colonel William Cook was the first to suggest warming rooms by means of metallic tubes filled with steam, fed from a boiler located outside the room.[48] According to Rumford, there had been many attempts to heat liquids by means of steam introduced into them. Most of these had failed due to the lack of information about heat transmission in liquids, particularly the fact that fluids were poor conductors of heat, so that heat could not be made to descend in them (no attempts had been made to agitate the liquid while being heated).[25] In his paper published on the subject Rumford showed that in order to carry on this operation successfully is was *absolutely necessary* that the tube conducting the steam should be located vertically to the surface of the liquid and open at the *bottom* of the vessel. In order to get the maximum benefit, it was necessary to properly insulate the tubes that carried the steam from the boiler to the vessel, to avoid all loss of heat from their surface. Rumford suggested that the best insulation consisted in enclosing the piping within square wooden tubes surrounded on every side by charcoal dust, fine sawdust, or even wool. His ideas were put into practice by several dye houses in Leeds, who reported that they led to a saving of about 2/3 of the heat spent when heat each vat by a separate fire.[25]

In 1814 Rumford reported his measurements of the heat condensation of water and aqueous solutions of alcohol[37] and of the heat capacity of various liquids (olive oil, linseed oil, naphtha, turpentine, alcohol, spirit of wine, and ethyl ether).[32] His results indicated that in the condensation of steam "1040 degrees of heat were released in the condensation of water".

Instrumentation

The many experiments carried on by Rumford on heat and its generation and transmission, led him to contrive two instruments, one measuring the amount of heat being processed (a calorimeter), and the other to measure very small temperature differences (which he named thermoscope).

The calorimeter was essentially a box filled with a known amount of water and provided with a serpentine tube through which the combustion products were made to pass. The temperature increase of the water was measured and served as a basis to the calculations. To cancel the effects of the outside temperature, Rumford started his calorimeter at a certain number of degrees below the external temperature, and ended it at the same number of degrees above the external temperature (Rumford neglected the changes in specific heat with temperature).

The thermoscope was actually a differential thermometer; its principal part consisted in a long glass tube curved at each end with very small glass tubes at its extremities. The straight middle portion of the tube was placed horizontally while its two extremities, culminating in the two globes, were turned upward so as to form two elbows at tight angle to the horizontal section of the tube. In the middle of the tube was a bubble of colored spirit of wine. The smallest increase of heat (temperature) in one of the balls drove the bubble toward the other. Rumford used his thermoscope in his experiments about photometry hygrometry, heat capacity, and heat transmission. The construction details and mode of operation were described in a separate paper (Rumford, 1806d).[31]

Glacier phenomena

During a trip made to the Glaciers of Chamouny, Rumford observed a very curious phenomenon. At the surface of a solid mass of ice, of vast extent and thickness, he discovered a pit, perfectly cylindrical, about 18 cm in diameter and more than 1.20 m deep, quite full of water. The guide told him that these cylindrical holes were known to form during the summer and freeze on the return of the winter. The quiescent mass of water, which constantly filled the hole, had necessarily to be at the temperature of freezing, since it was surrounded on every side by ice, but the pit went on increasing its depth during the whole summer. Hence the question: what was the origin of the heat that melted the ice continually at the bottom of the pit, and how it could it be that this heat acted on the bottom of the pit only and not on its sides[26]? Rumford believed that this curious phenomenon could be explained very easily. The warm winds, which in summer blew constantly over the surface of this column of ice-cold water, transferred a small amount of heat to the water particles coming in immediate contact with this warm air (the upper layer). Since water achieved its maximum density at about 4^0C, these particles were denser than the ones in the layers below and thus sunk slowly to the bottom of the pit where they came into contact with the ice and communicated to it the heat by which the depth of the pit was continually increased. He believed that the operation was exactly similar to that which took place in his experiment #17 described in a previous publication.[24]

Rumford thought that these results were closely connected to another phenomenon; the water at the bottom of all deep lakes is constantly at the same temperature (41 ^{0}F), summer and winter, without any sensible variation. This fact seems enough to prove that if there is any immediate trasnfer of heat between neighboring particles or molecules of water, gradually, or from one of them to the other, that transfer must be so extremely slow, "that we may safely consider it as having no existence, and it is within this limitation that he spoke of fluids as being non-conductors of heat." Hence his claim, that changes of temperature in *transparent* liquids had necessarily to take place at their surfaces.[24]

"In all the attempts to cause heat to descend in liquids, the heat unavoidably communicated to the sides of the containing vessel, must occasion great uncertainty with regards to the results of the experiment, and when that vessel is constructed of ice, the flowing down of the water resulting from the thawing of the ice, will cause motions in the liquid and consequently inaccuracies of still greater moment. When the thermometers immersed in a liquid at a small distance below its surface, acquired heat, in consequence of a hot body being applied to the surface of the liquid, that event is no decisive proof that the heat acquired by the thermometer is communicated by the fluid from above, downwards, from molecule to molecules, gradually; so far from being so, it is not even a proof that it is from the fluid that the thermometer receives the heat which it acquires, for it is possible, for aught we know the contrary, that it may be occasioned by the radiation of the hot body placed at the surface of the liquid".[24]

In a paper analyzing the phenomenon observed at Chamouny, Rumford described the additional experiments he had carried on to find the temperature of water at it maximum density. Judging from the constant temperature, which is found at all seasons at the bottom of deep lakes and the results of his experiments he concluded that water was at its maximum density when it is at 41 ^{0} F or 5 ^{0} C (not a bad approximation considering the rather simple equipment he used).[28]

Surface phenomena

According to Rumford, it was common knowledge that small bodies denser than water, such as very small grains of sand, fine fillings of metal, and small sewing needles, were able to float in the liquid. This phenomenon was assumed to be caused by air adhered to the floating bodies.[40] Rumford believe that this explanation was not necessarily true and decided to perform a systematic research on the subject. He first half-filled a wine glass with water and then poured on top of it a layer of sulfuric ether. Once the liquid was perfectly still he introduced through the ether, to a small distance from the water layer, a variety of objects heavier than water (a small sewing needle, tin globules, or mercury globules) and observed that these all these objects remained floating. Visual observation indicated that the globule seemed to be suspended in a kind of bag, a little below the surface of the water. Rumford now added a second globule and noticed that it immediately moved towards the first, with an accelerated motion until it fell down in the same cavity, which then become longer. Interesting enough, the two globules did not unite. Addition of a third globule led to rupture of the bag because it could not support the total weight. When this experiment was repeated with a larger mercury globule (about 1/40 or 1/50-inch diameter), the bag was not formed and the globule descended to the bottom of the glass. When the viscosity of the water was increased by the infusion of gum Arabic, the bag supported much larger globules. The same results were obtained by using essential oil of turpentine oil or olive oil, instead of ether. In order to discover with greater accuracy, the presence of a pellicle (thin skin) at the surface of the water, Rumford conducted another experiment using a cylindrical glass vessel 10 inches high and 1-2/3 inch in diameter, filled with water and ether as before. A mercury globule, pieces of extremely fine silver wire, and tin powder thrown into the vessel descended through the ether and floated on the surface of the water. When the whole was perfectly calm, Rumford turned the cylinder rapidly, three or four times round its axis, while keeping it in a vertical position. All the small floating bodies turned around along with the glass, and stopped when it was stopped; but the liquid water below the surface did not at first begin to turn along with the glass; and its rotational motion did not stop with the motion of the vessel. From these results Rumford concluded that there a real pellicle was present at the surface of the water, and was strongly attached to the sides of the glass, so as to move with it.[40]

In order to evaluate the resistance offered by the pellicle present on the bottom surface of a stratum of water to the passing of a solid body through it, Rumford repeated the first experiment, this time pouring first mercury in the wine glass, followed by water and ether, thus producing a three-layer arrangement. He now threw into a vessel a very thin spherule of mercury, which broke through the ether and water layers but stopped at the upper surface of the mercury. He found that moving the spherule and/or compressing it with a feather, did not change its spherical form, and refused to mix with the mass of mercury. The fast evaporation of ether, and its inability to support the lightest particles of a solid upon its surface indicated that the mutual adhesion of its particles was very small.[40]

Moisture

His 1787 paper Rumford studied the relation between the conducting power of substances commonly used for clothing and their power for absorbing moisture from the atmosphere.[39] He exposed different substances, (i.e., sheep and cotton wool, beaver fur, elder down, silk, linen, and silver wire), clean as much as possible, for twenty-four hours in the dry air of a very warm room, which had been heated every day for several months by a stove, with the last six hours the temperature being kept at 85 ^{0}F. After this period, he weighed equal quantities of each of the substances being tested, moved the samples to another room and exposed them for 48 hours to the air at 45 ^{0}F, weighted them again, and then removed and placed them in a very damp cellar where the temperature was also 45 ^{0}F, and the hygrometer indicated that the air was completely saturated. He hung in the room wet linen clothes in order to assure that the air remained as damp as possible during the following 72 hours. Afterwards the samples were weighed again. A table reporting the results of the three weightings indicated that those bodies, which were easily wet or easily absorbed liquid water were not those, which in all cases attracted the water vapor in the air with the greatest strength. For an initial weight of 1000 units, the weight after being exposed in a damp cellar, grew for sheep's wool, eider down, silk, linen, and cotton wool, to 1165, 1112, 1107, 1102, and 1082 parts, respectively. In orders words, sheep wool was the most absorbent of all the materials tested. Rumford remarked that "it was well known that woolen clothes, such as flannels, worn next to the skin, greatly promoted insensible perspiration, hence his question if this might arise from the strong attraction, which subsisted between wool and the water vapor which was continuously issuing from the human body? This effect did not depend entirely upon the warmth of the covering because the same degree of warmth produced by wearing more clothing of a different kind did not produce the same effect. The perspiration of the human body being absorbed by a covering of flannel was immediately distributed through the who thickness of that substance and by that means exposed to a very large surface to be carried off by the atmosphere, and the loss of this water vapor, which the flannel sustained on the one side, by evaporation being immediately restored from the other, in consequence of the strong attraction between the flannel and this vapor, the pores of the skin were disencumbered, and were continually surrounded by a dry, warm, and salubrious (healthy) atmosphere. Rumford expressed his surprise that the custom of wearing flannel next to the skin should not have prevailed more universally". He was confident that it would prevent a multitude of diseases. It was a mistaken notion that it was too warm clothing for summer; it was the warm bath of a perspiration confined by a linen shirt, wet with sweat, which rendered the summer heats so insupportable. Flannel promoted perspiration and favored its evaporation, with the resulting positive cooling effect.[39]

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Notes

[1] The ballistic pendulum, invented in 1742 by Benjamin Robbins (1707–1751), revolutionized the science of ballistics as it provided the first way to accurately measure the velocity of a bullet. Robins used it to measure projectile velocity in two ways. The first was to attach the gun to the pendulum and measure the recoil; the second was to directly measure the bullet momentum by firing it into the pendulum.

[2]. In 1781, Aimé Argand (1750-1803) invented a new type of lamp having a single wick and able to emit as much light as seven candles. Argand's design was based on drawing the air to the flame by a hollow cylindrical wick, which allowed it to flow both inside and outside the flame at the upper edge of the fuel-soaked wick, enclosed within a transparent glass chimney. This arrangement produced a steady flame of a brightness superseding all other lamps available at the time. The high density and viscosity of the oils available then forced Argand to locate the oil reservoir above the burner; eventually this problem was solved when kerosene became available about 1850.