# COUNT RUMFORD ON THE ART AND SCIENCE OF HEAT TRANSFER

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Abstract

Count Rumford, né Benjamin Thompson, had a highly productive and often controversial career. Though best known for his famous cannon boring experiments, he made important contributions to heat transfer. His quantitative and qualitative studies of conduction, convection and radiation led him to a number of important insights for the science of heat transfer. More an engineer than a scientist, he spent considerable effort applying his knowledge of heat transfer including clothing for all weathers, kitchen ranges, efficient pots and roasters, steam systems for comfort heating and manufacturing, pipe insulation and improved fireplaces. His important basic and applied research, and the diverse uses to which he was able to apply the knowledge he developed mark him as a key pioneer in the field of heat transfer.

"The science of heat is not only of great curiosity, from the multitude of astonishing phenomena it offers to our contemplation, but it is likewise extremely interesting from its intimate connection with all the useful arts, and generally with all the mechanical occupations of human life." (Rumford, vol. 2, p. 8)

## Introduction and Biographical Sketch

Benjamin Thompson, Count of Rumford, is a key figure in the early history of the science of heat transfer. In addition to the canon-boring experiment for which he is well known today, his long career in science often focused on heat transfer questions. Rumford was fascinated with the subject of heat and its applications in areas such as cooking, comfort heating and manufacturing. He correctly surmised that his studies of the three modes of heat transfer -- conduction, convection and radiation -- would be of great value to humanity.

Rumford was a product of his times -- soldier of fortune, engineer, scientist, civil servant, philanthropist, inventor, dietitian, landscape architect, social reformer, as well as the center of numerous political and scientific disputes. President Franklin Roosevelt stated that "Rumford together with Benjamin Franklin and Thomas Jefferson are the three greatest minds that the United States ever produced . . ." (Ewen, 1965), though that statement came before the conclusive evidence was revealed that he served as a spy for the British, while still living in America. Much is known about this controversial man. Biographies abound (Bradley, 1967; Brown, 1962; Brown, 1979; Ellis, 1875; Larsen, 1953; Sparrow, 1964, Thompson, 1935) and his collected scientific works, including those on social reforms, have been published, not once but twice (Rumford, 1968-1970; Rumford, 1875). (*Citation to his work in the present study are to the later collection).

Rumford was born Benjamin Thompson, in Woburn, Massachusetts in 1753. Figure 1 is a recent picture of his home, which is now a museum. His father, a relatively poor farmer, died before he was two, but his mother remarried shortly thereafter. His formal schooling was meager, as was the custom then in all but the wealthiest families. Unhappy at the thought of being a farmer, at age thirteen he was apprenticed to a merchant. Other apprenticeships followed, including one to a merchant in Boston, and one to a physician. He

Figure 1 Birthplace of Count Rumford, Woburn, Massachusetts 1753.

had a brief career as a school teacher, first in Massachusetts and later in Concord, New Hampshire. It was in Concord in 1772 where he met and married his first wife, a wealthy widow fourteen years his senior. With the wealth he acquired through marriage he gave up school teaching and received an appointment from the governor as a Major in the New Hampshire Militia. His loyalties were strongly with the Crown and he served as a spy, using invisible ink to transmit some of his messages for the British Army. In 1775, he fled to avoid arrest by American patriots and went over to the British in Boston.

The next year, having traveled to London, he was befriended and employed by the Secretary to the Colonies, George Germaine. While serving in the colonial office he started some of his first experiments. He rose rapidly as a favorite of Lord Germaine to become Undersecretary for the Northern Provinces. He returned to America (under some cloud of suspicion) following his purchase of a commission as Lt. Colonel and Commander of a cavalry regiment which he was to command. He served, with some distinction, against the American patriots, first in South Carolina and later on Long Island where he embittered the local population by his actions. He returned to London where he stayed only long enough to be promoted to full Colonel and retire on half pension. He then set off to the continent to seek his fortune. Figure 2 is a portrait of Thompson at the age of thirty done by Gainsborough.

Thompson caught the eye and favor of Carl Theodor, Elector of Bavaria. He returned briefly to England to be knighted by George III, and then

Figure 2 Benjamin Thompson, later Count Rumford, 1783.
Painted by Thomas Gainsborough, 1727-1788.
Courtesy of the Harvard University Art Museum.

served the Elector in Munich from 1784 to 1798 in a variety of public offices, which afforded him the means and time to pursue his scientific endeavors. It was during this period that he did much of his research on heat transfer. In addition to his scientific and technical studies he made a number of sweeping military and social reforms. He revamped the army, providing decent pay, education for the children of soldiers, and work in WPA-type projects. He was a strong believer in social order, and has been called "instinctively a totalitarian, . . . a believer in the ordered state, in the planned and efficient economy, in the detailed regulation of the common life." (Shapely, 1953) In almost a single day, he cleared the streets of Munich of beggars who were some four or five percent of the population. He set them up in Houses of Industry where they were taught and encouraged to work and become independent. He fed them simply and efficiently through kitchens he designed and menus he developed.

Rumfords work and writings cover a variety of subjects including ballistics, photometry, social planning, and even recipes --Rumford soup is still an item that one comes upon occasionally -- as well as studies related to "Heat". He was a staunch advocate of coffee and went into great detail on how best to prepare it. In 1792, he was made a Count of the Holy Roman Empire by Carl Theodor. He chose the title Graf von Rumford or Count of Rumford using an early name of the town in New Hampshire where he was first wed.

Rumford returned to England in 1798 and was principal founder of the Royal Institution of Great Britain. He moved on to Paris in 1802. A few years later he entered what was to be an unhappy marriage with Madame Lavoisier, whose famous husband had been guillotined. Rumford became a fan of spas and baths as a means of curing a number of ills. As a philanthropist, he donated significant funds to set up scientific medals in both England and the United States. He lived as somewhat of an eccentric, wearing white clothing to reduce heat emission during the winter and had extra wide wheels put on his carriage to smooth the ride on the rough streets of Paris. Figure 3 shows Rumford in 1808 at the age of 55. He died at the age of 61 in Auteuil, France.

During his life Rumford was involved in much social and personal controversy. His first wife was embittered at his departure and never saw him after he left in 1775. He fought publicly with his second wife from whom he parted. He served as a spy against his fellow Americans, perhaps as a spy for the British against the Bavarians, and was suspected of being a spy against the British. He angered many of those he worked with, including most of the leading citizens of Bavaria, though years after his death a statue of him was put up there (Figure 4 shows a replica in his hometown of Woburn.) He left England after arguing with some of his fellow founders and officers of the Royal Institution. He had a number of scientific disputes about priority,

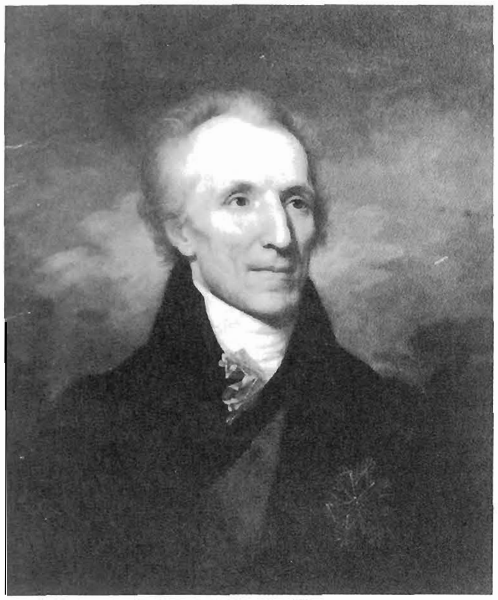


Figure 3 Rembrandt Peale's portrait of Count Rumford 1806. Courtesy of the American Academy of Arts and Sciences.

Figure 4 Replica of the Munich statue of Count Rumford erected in his home town of Woburn, Massachusetts

particularly with John Leslie. Though he had many enemies, when he wished he could be extremely charming, as when he won the favor of the Governor of New Hampshire, and of Carl Theodor, Elector of Bavaria, whom he served well. Yet he seemed to have little love for his fellow man.

Count Rumford's formal education was minimal, yet he became a lucid writer, and an articulate and careful speaker. Though he did attend some lectures of John Winthrop, Professor of Natural Philosophy at Harvard, his scientific knowledge came from self-directed reading and his own experiences and reasoning power. He was eager to try small experiments, even as a teenager. He attempted, although unsuccessfully, while in America to publish two scientific papers, one on a malformed fetus and another on the Aurora Borealis. His first significant research was his studies on gun powder and ballistics in England while attached to the British Navy. Although he did research in many other areas as well, the present study is restricted to his work on heat -- primarily the transfer of heat by different mechanisms.

Research Studies on Heat

A. Early Interest in Heat and Canon-Boring Experiment

A young mind is open to many ideas and when it takes one in, it sometimes holds it so tightly that it can shape a life, for good or for bad. To some extent this was true for Benjamin Thompson, who when sixteen read the book by the Dutch scientist Boerhaave, A New Method of Chemistry, particularly the chapter "Fire." Rumford recounted, "To engage in experiments on heat was always one of my most agreeable employments. This subject had already begun to excite my attention when, in my seventeenth year, I read Boerhave's [sic] admirable Treatise on Fire. Subsequently, indeed, I was often prevented by other matters from devoting my attention to it, but whenever I could snatch a moment I returned to it anew, and always with increased interest." (Rumford, vol. 1, p. 443)

The prevailing theory of heat during the much of the 18th and 19th centuries was the caloric theory. Though somewhat disparate definitions were used even by its advocates, the theory generally considered heat as a subtle self-repulsive fluid which could flow from one body to another. In contrast, Boerhaave considered that, "motion of the particles of ordinary matter (conceived as a vibration)...was responsible for the phenomena of heat." (Fox, p. 12, 1971) It was this idea of heat as related to motion and not as a subtle fluid that drove Rumford, a strong opponent of the caloric theory, to his most famous experiment.

Rumford put a special boring tool in a canon which he turned. He found that the water surrounding the canon continued to boil as long as the canon was kept turning. He commented that "heat generated by friction, in these experiments, appeared evidently to be inexhaustible. . . it appears to me to be extremely difficult, if not quite impossible, to form any distinct idea of anything capable of being excited and communicated in the manner the Heat was excited and communicated in these experiments, except it be MOTION." (Rumford, vol. 1, p. 22)

It was his abiding interest in heat that had a strong influence on his studies in heat transfer. He made many studies of phenomena in conduction, convection, and radiation. He was the first heat transfer researcher to obtain considerable quantitative data, unfortunately little of which can be used directly today. From measurements and his qualitative observations he made a number of valuable, and some incorrect, deductions.

"It is only by careful observation of the phenomena which accompany the heating and cooling of bodies, that we can hope to acquire exact notions of the nature of heat and its manner of acting," (Rumford, vol.2, p. 1)

B. Conduction Heat Transfer

In some of his earliest experiments on heat transfer he designed an apparatus for measuring the transfer of heat through different materials. This consisted of a spherical (later cylindrical) glass container with a thermometer bulb placed near its center. Different materials could be placed in the enclosure. He called these devices (Figure 5) passage thermometers because they measured the passage of heat from outside the enclosure, to the thermometer at the center. He would maintain the entire passage thermometer in a medium at a fixed temperature, often boiling water, until it came to steady state, as determined by the thermometer reading; then he would quickly immerse it in a bath at a different temperature (e.g. an ice bath) and measure the

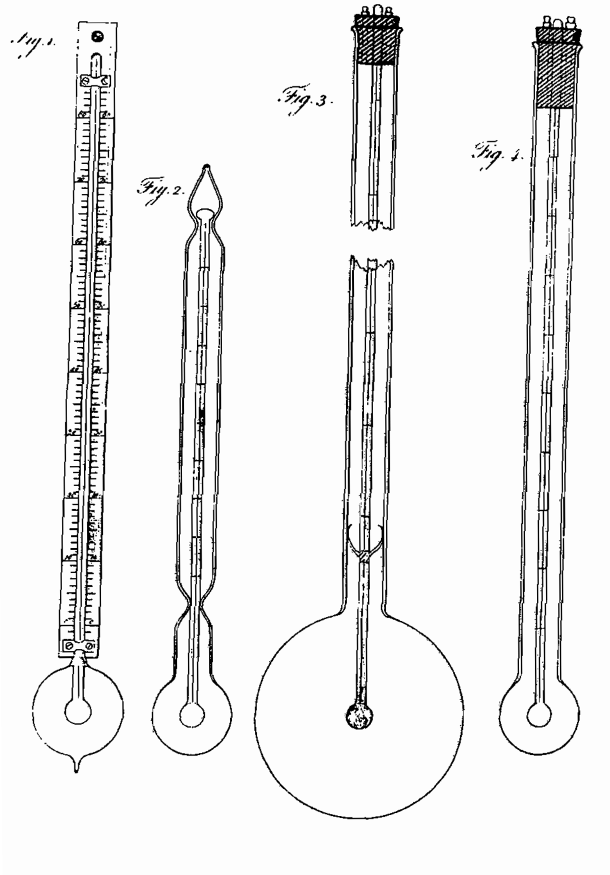



Figure 5 Passage thermometers (Rumford, p. 52, vol. 1)

time it took for the thermometer in the center of the globe to go through different temperature ranges. He made a number of measurements using these devices holding, air, water, and insulating materials (sheeps' wool, hares' fur, silk, eider down, etc.). A simple analysis today shows that for pure fluids in the container the Rayleigh number is sufficiently high that convection would tend to mask the pure conduction phase of heat transfer. In addition, the heat capacity of the materials must be considered in analyzing the results so not only the conductivity (which Rumford assumed was being determined) but also the thermal diffusivity must be considered. The importance of convection in the passage thermometer, as we will see below, is a conclusion that Rumford himself reached in the course of continuing his experiments. However, let us examine further the experiments on conduction in which he used different insulating materials.

He understood how the conductivity of a material influenced the sensation that one felt touching it. Thus he concluded that mercury appears to be much hotter or colder to the touch than water when it is at the same temperature because of its greater ability to communicate heat which depends on the "conducting power" of the material. Since he was interested not only in housing and feeding the poor and the soldiers in Munich, but in clothing them as well, he was very interested in the insulating properties of different materials, which he studied using his passage thermometers. He found that adding small amounts of materials (e.g. raw silk or eider down) would increase the time it took the thermometer to change its temperature over the range studied. He attributed this, quite cleverly, to the impact of the air within the material and the necessity of having small volume spaces for the air. He went on to argue that "furs which are the finest, longest, and thickest, are likewise the warmest." (Rumford, vol.1, p. 111)

In his experiments and studies on conductivity in fluids, Rumford drew some rather extreme and incorrect conclusions about the nature of conduction. He correctly found, as we shall discuss, that convection plays a major role in the transport of heat by fluids. Yet, on observing this, he incorrectly came to the conclusion that fluids were non-conductors of heat. In his later writings he would somewhat modify his view of the non-conducting nature of fluids, but he always thought of them having a different type of conduction mechanism than solid materials. He believed that if they were conducting, their conducting power was much less than that of solids. In his early work he was so certain of this propriety of fluids that he believed that for fluids "among these particles themselves all interchange and communication of Heat is absolutely impossible." (Rumford, vol.1, p. 122)

This apparent lack of conducting power was heightened in Rumfords' mind by a number of anecdotal experiences which he recounted. Thus once leaving a bowl of rice soup on an oven top for an hour he "went up to it and took a spoonful of the soup, which I found almost cold and quite thick. Going, by accident, deeper with the spoon the second time, this second spoonful burnt my mouth." (Rumford, vol. 1, p. 122-123) This and other accounts concerning apple pies and hot almond mixtures, reinforced his belief in the non-conducting power of liquids. In a related account he told of walking on the sand at a thermal spa. The top of the sand and water were quite cold, but "running the ends of my fingers through the cold water into the sand, I found the heat so intolerable that I was obliged instantly to remove my hand." (Rumford, vol. 1, p. 123) He again concludes that the transport of heat would only be due to buoyancy-driven flow and that the liquid would not conduct heat. In an experiment with a passage thermometer he used a stewed apple mixture and measured the fraction of water in the mixture. In finding the percentage of water to be almost 100% he states that the fibrous material in apples decreases or limits the motion of the water and thus bring the conducting power down to zero. If he had only said down close to pure conduction we would have been able to agree with him. Even so, this insight into the importance of reducing mass motion to reduce heat transfer was very insightful.

C. Convection

"In the course of a set of experiments on the communication of Heat, in which I had occasion to use thermometers of an uncommon size (their globular bulbs being above four inches in diameter) filled with various kinds of liquids, having exposed one of them, which was filled with spirits of wine, in as great a heat as it was capable of supporting, I placed it in a window, where the sun happened to be shining, to cool; when casting my eye on its tube, which was quite naked (the divisions of its scale being marked in the glass with a diamond), I observed an appearance which surprised me, and at the same time interested me very much indeed. I saw the whole mass of the liquid in the tube in a most rapid motion, running swiftly in two opposite directions, up and down at the same time . . . I found that the ascending current occupied the axis of the tube, and that it descended by the sides of the tube." (Rumford, vol. 1, pp. 124-125)

He described quite aptly convection and its cause, "the immediate cause of the motions in a liquid, which take place on its undergoing a change of temperature, is evidently the change in the specific gravity of those particles of the liquid which become either hotter or colder than the rest of the mass, and as the specific gravities of some liquids are much more changed by any given change of temperature than those of others, ought not this circumstance (independent of the more or less perfect fluidity of the liquid) to make a sensible difference in the conducting power of liquids?" (Rumford, vol.1, p. 189)

This discovery of motion in fluid due to solar heating excited him greatly and led to more visualization studies on convective motion (The term convection was not, however, introduced until 1834 by William Prout). Although buoyancy-driven motion had been observed earlier in connection with atmospheric flows, this was the first recounting of it for heat transfer in general, and in liquids in particular. Having this mechanism for heat transport is what convinced Rumford that other forms of heat transfer did not exist in fluids and that they were "non-conductors".

To show more clearly buoyancy-driven flow he filled a cylindrical glass tube, about 3/4 inches in diameter and 12 inches long, with a dilute saline solution mixed with ground amber powder. He adjusted the density of the liquid so that the amber was essentially neutrally buoyant by adding pure vegetable alkali. On plunging the apparatus into water that was almost boiling, he observed a rapid upward current near the side of the tube and a downward current near the center. The velocities diminished as the saline solution grew to a uniformly warm temperature. On removing the glass cylinder from the hot water and holding it vertical, the direction of the currents reversed; that is the ascending current was at the axis of the tube. This clear view of buoyancy-driven flow preoccupied many of his future experiments.

Following his observation that flow could be driven by buoyancy forces due to temperature differences, he tried to determine if heat could be transported downwards through a fluid. In these experiments he did not generally have a simple closed layer, but a hot body immersed into a fluid; he then measured the temperature further down in the fluid. With liquids he observed that the temperature some distance below the heated object did not rise so he concluded that no heat was conducted through the fluid. In another set of experiments he used the apparatus shown in Figure 6 to observe whether or not the conical tip of ice would melt while oil or mercury were in the layer into which a hot vertical rod of iron was inserted. The tip would not melt.

His experiments led him to conclude that "water is a perfect non-conductor of Heat, and that Heat is propagated in it only in consequence of the motions which the Heat occasions in the insulated and solitary particles of that fluid." (Rumford, vol. 1, p. 187) Rumford went further, saying air and even water were non-conductors. He concluded that all fluids including mercury were non-conductors. He was misled by several factors. One is the relatively low thermal conductivity of many fluids and another is the influence which convection had in masking heat transfer due to conduction. For example, in the annulus between two concentric horizontal cylinders, with the inner one heated, the lower surface of the outer cylinder receives much less heat when convection takes place than a simple one dimensional conduction calculation predicts. This is due to the flow of cooler fluid down along the surface to the bottom of the outer cylinder. His discovery

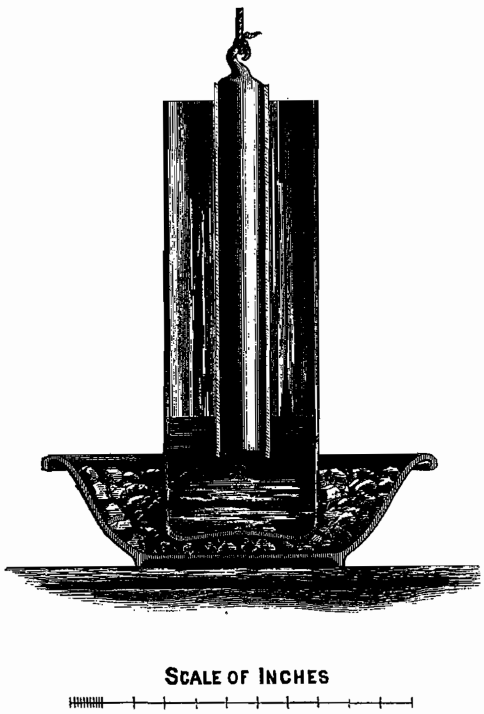



Figure 6 Apparatus for studying the downward flow of heat in liquids (Rumford, p. 401, vol. 2, 1876 Collected Works)

of heat transfer by mass motion in fluids blinded him from seeing the reality of finite conductivity in all materials.

Rumford went on to examine the influence of the density maximum of water slightly above its freezing point and probably was the first to argue its importance in preventing lakes from freezing solid. As was common in those days he attributed the beneficial aspects of Laws of Nature to the Deity, arguing that the density maximum in water, which made it difficult for lakes to freeze throughout their volume was, "a more striking or more palpable proof of the wisdom of the Creator, and of the special care he has taken in the general arrangement of the universe to preserve animal life, than this wonderful contrivance . . ." (Rumford, vol.1, p. 190) Later he concluded that "a belief in the existence of a Supreme Intelligence, who rules and governs the universe with wisdom and goodness, is not less essential to the happiness of those who, by cultivating their mental powers, have learned to know how little can be known." (Rumford, vol. 1, p. 213)

Rumford enhanced his ability to visualize the fluid motions in convection by designing and constructing a special experimental apparatus. This consisted of an enclosed double pane window, 1 inch gap, 13 inches high by 10½ inches wide, filled with a saline mixture and yellow amber. Placed in a southeast exposure there was a temperature difference across the layer due to the warm air inside the room and the cold air outside. In his earlier experiments he observed what was essentially a single cell or roll, with flow in the upward or downward direction except at the ends of the container. Here he observed a series of cells at different heights with strong horizontal motions which he compared to atmospheric currents and winds generated by solar heating.

D. Radiation

Rumford's greatest contribution to the science of heat transfer was probably his observations of thermal radiation. One of his earliest experiments was concerned with the ability of a vacuum to conduct heat. At the time of his work, pumps were not able to provide very high vacuum, so he resorted to creating a "Toricelli vacuum". Taking one of the passage thermometers used in studying the conducting power of different materials, he filled it with mercury, connected it to a tube and inverted it till the mercury ran out into a barometer column. Then he sealed off the glass tube leaving in place only the low pressure mercury vapor. A calculation for the system used indicates that this would yield a Knudsen number sufficiently high that there would be little conduction heat transfer. Indeed he found that the conducting power (in this case really radiation heat transfer) as measured in the passage thermometer, was considerably less than that of atmospheric air. He found to his surprise, that when he reduced the pressure of air in the passage thermometer using a pump which could reduce the pressure to a few percent of an atmosphere, the conducting power of the low pressure air, was only slightly less then that of atmospheric air. The Knudsen numbers in those experiments were relatively small.

Rumford was interested in the practical insights provided by heat transfer, such as the insulating properties of clothing. He designed an instrument (Figure 7) which enabled him to measure these properties for various materials. Today we would call this a calorimeter (which would probably not please Rumford, a staunch apponent of the caloric theory). It contained water in a large brass cylinder with a thermometer inserted into it. The rate of change of the temperature of the (initially hot) water was determined with various materials wrapped around the cylinder. Rumford cited Newtons Law of Cooling which he used to get the conducting power of the wrapped materials. Perhaps the most interesting test was when he wrapped a layer of linen around the cylinder; he observed that the water cooled more rapidly than when the linen was not there. He deduced that this was due to the effect of the linen on the nature of the surface and the "calorific rays"(radiation) leaving the cylinder. He went on to try different experiments where he blackened the bare cylinder and roughened the surface, each of which caused a greater rate of temperature decline than occurred with the bare shiny brass.

Rumford next designed a precision instrument (Figure 8a) to study thermal radiation. He called it a thermoscope; it is essentially a differential thermometer. The thermoscope consists of two

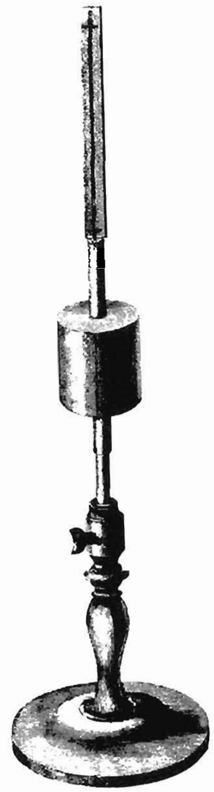


Figure 7 Calorimeter to measure heat loss of insulation wrapped around brass cylinder filled with water (Rumford, p. 327, vol. 1)

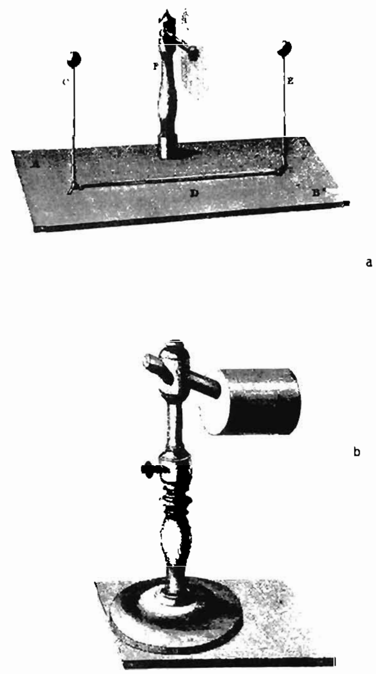



Figure 8 Thermoscope (a) and Isothermal (b) cylinder for studying characteristics of thermal radiation (*Rumford, p. 351, vol. 1*)

glass spheres connected by a "U" tube of glass, the diameter of the spheres being of the order of 1½ inches and the diameter of the glass tube about 1/16 of an inch. The fluid in the instrument was near-atmospheric-pressure air and he inserted a small "bubble" of alcohol in the horizontal span of the tube. Slight heating of one of the balls (each filled with air), relative to that of the other one, moves the bubble away from the warmer ball towards the cooler one. The system is indeed very sensitive and a calculation indicates a motion of the bubble of approximately 45 mm for a temperature difference between the two globes of 1°C. This was sufficiently large, that a number of observations could be made of the relative thermal radiating powers of different materials at different locations and at different temperatures.

Note that in the instrument he put a screen to separate the two spheres. Generally, screens were put around the entire apparatus to prevent the influence of extraneous sources of thermal radiation, including the experimenters. The spheres were painted black with India ink to make them more sensitive. Isothermal cylinders (Figure 8b), filled with water had a single flat surface at the end of the cylinder exposed to one of the spheres. He found that the amount of radiation (calorific rays) emitted was dependent on the nature of the surface, and surfaces which appeared to the eye to reflect light, also tended to give off fewer calorific rays. He found, for example that a brass surface, blackened by a flame gave off five times as many calorific rays as one which had been cleaned and well polished. Placing near one of the two globes of air, two cylinders, one being at a temperature above the room air and the other being at approximately equal temperature below the room air, he found that the effects of the two cylinders cancelled each other (the bubble did not move), as long as the same type of surface, shiny or black, was on each of the cylinders.

Rumfords' experiments led him to believe in the existence of "frigorific rays", not the mere absence of "calorific rays". These were given off by cold surfaces and to him were just as real as calorific rays. In this, as in many other deductions he made, he was quite stubborn and insistent on its scientific validity. His stubbornness in many ways was an asset, but in this case, as in his conclusions on the non-conducting nature of fluids, it was a liability. Of course with accumulated knowledge we can now understand radiation interchange and the need for an energy balance in heat transfer. It is doubtful that any of us would have reached this conclusion 200 years ago.

Rumford understood the $1/r^2$ law and the effect of distance of the emitter on the calorific rays striking the receiver. His observations on the emissive power of surfaces, and its relationship to absorptivity are significant. The nature of the surface as an important factor in affecting calorific rays was well appreciated by others when he introduced it. He also applied this in many practical devices he invented or perfected.

It should be noted that at approximately the same time, John Leslie in Scotland made and used a similar differential thermometer to study radiation properties of surfaces. Rumford became entangled in a priority dispute which was never fully resolved, though certainly his thermoscope experiments appears to be a logical extension of his earlier works.

Rumford designed a small calorimeter (Figure 9) to study the absorption of solar rays. Exposing the calorimeter to sunlight he could measure the temperature rise in the device which contained a number of flat silver threads. Using different surfaces on which the solar rays fell he found that a blackened surface tended to cause the material to increase in temperature more rapidly than a shiny surface. In a related experiment, using solar input with a fixed aperture and lenses which caused the sunlight to converge or diverge on a calorimeter, he found that the total input of heat provided over a given period of time was the same for the given aperture from converging, diverging or straight rays. Though obvious today, it was surprising to many at that time, because of the extremely high temperatures obtainable from converging solar rays.

Rumford made some very insightful observations about the relationship between calorific rays and light, "there are so many striking analogies between the rays of light and those invisible rays which all bodies at all temperatures appear to emit, that we can hardly doubt of their motions being regulated by the same laws. . . . Perhaps there may be no other difference between them than exists between those vibrations in the air which are audible and those which make no sensible impression on our organs of hearing. . . if our eyes were so constructed as to see all the rays which are emitted continually, by day and by night, by the bodies which surround us, we should be dazzled and confounded by that insupportable flood of light poured in upon us on every side." (Rumford, vol. 1, pp. 416)

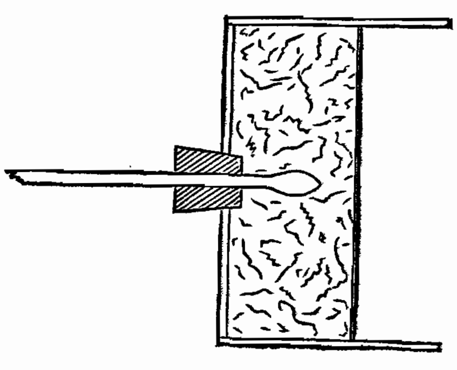


Figure 9 Calorimeter for studying absorption of solar rays (Rumford, p. 483, vol. 1)

This view that that light and emitted thermal radiation are essentially the same, only differing in frequency or wave length, was a key deduction. It anticipated, and helped lead to, our modern understanding of radiation. Rumford derived this insight principally from his observations of the relative reflecting and absorbing powers of different surfaces.

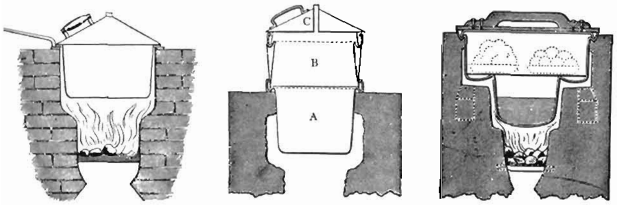
E. Applications of Heat Transfer

"Heat is employed in such a vast variety of different processes, in the affairs of life, that every new discovery relative to it must necessarily be of real importance to mankind; for, by obtaining a more intimate knowledge of its nature and mode of action, we shall no doubt be enabled not only to excite it with greater economy, but also to confine it with greater facility, and direct its operations with more precision and effect." (Rumford, vol. 1, p. 323)

Rumford was indeed more engineer than scientist. Applications often came to mind; "The sublime in science consists in employing it to extend the power and increase the innocent enjoyments of the human race." (Rumford, vol. 1, pp. 301) He would often write, in one form or another, on the importance of the applications of his heat transfer studies. "There is no branch of the physical sciences which is so intimately connected with all the every-day occupations of man as that of Heat, and consequently there is no one of them which interests him so closely." (Rumford, vol. 1, p. 301) He was always seeking uses which could be made of his basic research in the thermal sciences. Those for which he is most known relate to the development of clothing, cooking utensils, heating pipes, manufacturing including brewing and drying, insulation, and fireplaces.

We have already mentioned a number of his experiments on the insulating power of different materials used in clothing. He was interested in the importance of weave and density of material and compared the insulating powers of man-made fabrics and natural furs. This was important for clothing the soldiers and the poor in Munich whom he brought into his Houses of Industry. In those houses he experimented on a number of thermal applications, in particular relating to large kitchens which he designed.

Rumford developed ranges which minimized the amount of wood for cooking, in contrast to the common open fire with a pot hanging over it. In addition to radiant heat the hot gases could be ducted around his pots. He also developed a double boiler to conserve thermal energy. He concluded that the key element in cooking was to maintain the temperature at a certain level and that continually adding heat to have a mixture boil more rapidly, was a waste of fuel. His studies on radiation convinced him that a proper pot would have a blackened bottom surface, often occurring naturally with coal or wood fires, which would enhance the transport of heat by calorific rays, but the pots should have shiny sides and tops to diminish the heat loss by radiation. Samples of some of the pots, he developed are shown in Figure 10.




a. b. c.

Figure 10 Rumford designed cooking pots, double boiler, and steamer (Rumford, pp. 249, 266, 270, vol. 3)

Rumford was interested in the use of steam as a medium for transporting thermal energy from one place to another. He brought in a number of applications for controlling steam for comfort, including careful design of the slope of the heating pipes and their insulation including a reflective outer coating. He was interested in direct contact heating and described how steam should be introduced at the bottom of a layer of liquid through a vertical steam pipe, in order to promote better mixing of the different temperature fluids. He brought steam heating to bear in a number of applications, including brewing, dyeing, hot baths and kitchens, drying systems for linen and paper manufacturing, as well as comfort heating. He gave explicit instructions on how to construct many of these devices, including the necessity of safety valves both to protect against high pressure and vacuum.

His design of the heating system for the Royal Institution not only used steam, but also considered the problems of cold air coming down from windows and the advantages of using double windows to enclose a layer of insulating air. Central heating, however, was not the rule in England and Europe during Rumfords' time, in particular not in London where open fireplaces were common. He put considerable effort in making major changes in fireplace design. At one time he wrote that he had personally changed the design of 500 already installed fireplaces and he later added many more to this number. One key problem with fireplaces then, and to some extent today, is the smoke that can flow back into the room in which the fireplace is located; a second is that they are inefficient in heating a room. Here Rumford brought his deep knowledge of buoyancy driven flows and radiation heat transfer. Figure 11 shows how he took a more or less standard-design fireplace and modified it to have a significant impact on both of these problems. In terms of smoke flow, he brought the throat of the chimney down much closer to the hearth, made the throat smaller and introduced the smoke shelf which significantly decreased the flow of smoke back down the chimney caused by outside wind currents. He rounded off certain sections which then afforded a better flow of air into the fireplace. He argued for the need of bringing in outside air, specifically to provide the ventilation for the fire, as opposed to using the warm air in the room. He observed that in homes that were reasonably well sealed, the problems of downflow of air in the chimney could be quite serious. He designed several new fireplaces with separate ducts to bring outside air into the fireplace, to eliminate this problem. He considered the need for materials in the fireplace that would reflect well the calorific rays given off by the flames and also adjusted the angle of the walls in the back of the fireplace to enhance radiation into the room.

It has been pointed out by more than one person that many of the concepts he developed for fireplaces have unfortunately been forgotten by some present day designers. Yet, the smoke shelf, the damper which he also championed, as well as a door cover on the fireplace are widely used today. He recognized that calorific rays were the key mechanism by which a fire communicated heat to a room and that the rays did not heat the air directly, but rather the absorbing material-walls, furniture, people, etc. they strike. His study of fireplaces was a typical extension of his practical approach, "Having long been accustomed to consider the management of heat as a matter of the highest importance to mankind, a habit of attending carefully to every circumstance relative to this interesting subject that occasionally came under my observation soon led me to discover how much this science has been neglected, and how much room there is for very essential improvements in almost all those various operations in which heat is employed for the purposes of human life." (Rumford, vol. 2, p. 310)

## Conclusion

Rumford was not a great theoretician. He had little formal training in mathematics and science as was evident in some of his disputes. He was, however, a great observer, be it of the Revolutionary forces training in Massachusetts, which he reported on to the British, or the motion of fluids in differentially heated layers. He was quick to recognize important physical phenomena observed in every-day life. From a variety of specially designed experiments, instruments, and apparatus he was able to come up with key concepts related to heat transport phenomena.

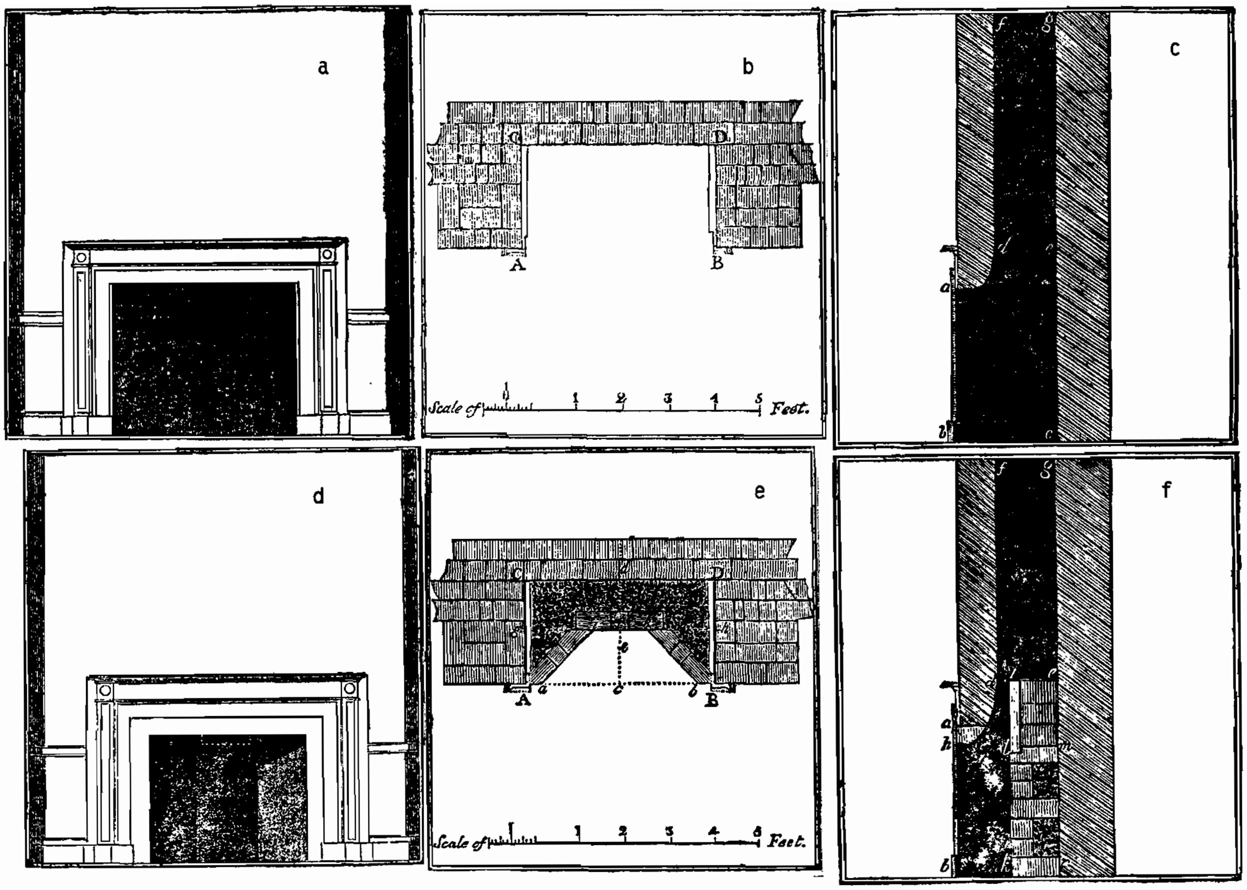



Figure 11 Before (a, b, & c) and after (d, e, & f) sketches of Rumford fireplace modification (Rumford, pp. 285, 287, and 289, vol. 2)

Even though not all of the concepts he deduced were correct, his fertile imagination, and the scope and impact of his research and writings played a major role in the history of heat transfer. His observations on convection, conclusions about the influence of the density maximum in water, experiments on thermal radiation and the many devices and systems he designed for efficient heat transfer applications were important developments. Some two hundred years after his major research, we would do well to concentrate on his many positive contributions to science, technology and society, and not his flaws of character, which have been popularized so much. Reversing Mark Antony, let us remember the good that Rumford did, and let the evil be interred with his bones.

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Professors Warren E. Ibele and Edward T. Layton provided a number of suggestions which were incorporated into the final draft of this paper.

TABLE 1
Chronology of Benjamin Thompson - Count Rumford

| | |
|---|---|
| 1753 | March 23, Born<br>Woburn, Massachusetts |
| 1766 | Apprenticed to merchant<br>Salem, Massachusetts |
| 1769 | Employed by Dry Goods Merchant<br>Boston, Massachusetts |
| 1770 | Studied medicine with physician<br>Woburn, Massachusetts |
| 1771 | Attended some lectures on Natural Philosophy at Harvard by Professor John Winthrop |
| 1771-72 | Taught school<br>Wilmington and Bradford, Massachusetts |
| 1772 | Teacher<br>Concord, New Hampshire |
| 1772 | November 14, married Sarah Walker Rolfe<br>Concord, New Hampshire |

1774 Daughter Sarah born
Concord, New Hampshire

1775 Served as a spy for the British Army
Departed for London

1776-80 Appointed to Office of the Secretary of the Colonies. Served as Secretary of Province of Georgia and eventually Undersecretary of the Northern Dept. of American Colonies-London, England

1778 Experimented with the use of gun powder and ballistics

1779 Elected Fellow of the Royal Society of London

1781 Obtained Commission as Lt Colonel, Commander of King's American Dragoons (a regiment he raised)

1781-83 Served in South Carolina and later on Long Island, New York

1783 Returned to England. Promoted to full Colonel with half pension

1784 Traveled to Continent seeking position

1784 Knighted by King George III

1784-98 Served Carl Theodor, Elector of Bavaria and the Palatinate, first as Aide de Camp; later Champberlain, Lt. General, Minister of War, and Minister of Police in Munich. During this period most of his research on "Heat" was performed.

1792 Named Count of the Holy Roman Empire-Graf von Rumford (Count of Rumford or Count Rumford) from the old name of Concord, New Hampshire

1798 Returned to live in England

1800 Principal founder of the Royal Institution of Great Britian

1802 Moved to Paris, France

1805 Married Madame Lavoisier
(widow of famous French chemist)

1809 Separated from second wife

1814 August 21, died
Auteuil, France

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