Isaac Newton and Heat Transfer

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An attempt is made to provide historical perspectives on the influences of Newton's law of cooling (1701) on the development of heat transfer theory. Newton's cooling law provides the first heat transfer formulation and is the formal basis of convective heat transfer. The cooling law was incorporated by Fourier (1822) as the convective boundary condition (Biot number) in his mathematical theory of heat conduction. The decisive step in the application of the concept of heat transfer coefficient occurred with the publication of the "basic law of heat transfer" by Nusselt in 1915. Newton's law is valid only for forced convection with constant physical properties. The close relationships for various heat transfer theories are pointed out. Heat transfer phenomena can also be classified based on the relationship between surface heat flux and temperature difference as a driving force.

The actions of gravity and heat are universal phenomena. Heat, like gravity, penetrates every substance of the universe, its "rays" occupy all parts of space, as noted by Fourier in 1822. Newton is credited with the discovery of the law of universal gravitation in 1685, and thus the generalization of the laws of mechanics on earth and in the heavens. In 1701 Isaac Newton published anonymously (in Latin) a pioneering work entitled "Scala Graduum Caloris" ("A Scale of the Degrees of Heat") [1]. Here, the first theoretical rate equation in the history of physics for heat transfer between a heated object and fast flowing fluid, based on the temperature difference as a driving force, now universally known as Newton's law of cooling, was enunciated.

The pursuit of the nature of heat ranges from the period of speculation by the early philosophers from 600 B.C. to 1600 to the period 1600 to 1800, which represents the dawn of the science of heat. In the eighteenth century the caloric theory (heat as a substance) dominated.

Incidentally, Newton's concept of "ether" and his emission theory of radiation had a considerable effect on the development of the concepts of phlogiston (G. E. Stahl) and calorique, the caloric theory, (W. Cleghorn) in later years. The dynamical theory of heat emerged by the middle of the nineteenth century, with the establishment of the first and second laws of thermody-

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namics. The most fundamental concepts in the description of heat phenomena are temperature and heat. It took an unbelievably long time in the history of science for these two quantities to be distinguished, but once the distinction was made, rapid progress resulted. Our highly subjective sensation of touch for hot and cold is rather qualitative and can also be confused by the simultaneous action of temperature and heat.

Newton's law of cooling is usually discussed in textbooks on "heat" published during the period 1800–1950 and in engineering heat transfer texts published in this century. Newton's original paper (1701) is also readily accessible [1, 2]. The following remark by Grigull [3] is of special interest here: "Every engineer knows Newton's 'Law of Cooling', the formal basis of convective heat transfer, but only few know the origin of this law and hardly anybody has read the original paper. Newton's motive for undertaking this unique work in thermometry is hard to establish. However, it is not unlikely that Newton's alchemical experiments inspired him to regard the melting- and freezing-points as fixed-points, and to base upon these a temperature scale."

Ironically, the same remark may apply also to Newton's classic monographs, *Principia* (1687) [4] and *Opticks* (1704) [5]. However, Newton's historical monographs are known to be difficult to understand. The purpose of the present article is an attempt to present historical perspectives of Newton's law of cooling from the viewpoints of review, observations, and influences on heat transfer theory. The portraits in Figure 1 serve to show the time period for the development of the science of heat. Figure 2 depicts Newton's famous apple episode.

NEWTON'S LAW OF COOLING AND TEMPERATURE SCALE (1701)

Historical Background

The foundation of mechanics was finally established by Galileo and Newton over about 100 years. In contrast, the period from Galileo's thermoscope in 1593 to the final establishment of the first and second laws of thermodynamics in 1850 is over 250 years. Newton's thoughts on heat and radiation are described in *Principia* (Vol. 2, pp. 521–522. [4] and *Opticks* (Queries 1–31, pp. 339–405 [5]. The development of the concept of heat from the fire principle of Heraclitus through the caloric theory of Joseph Black is well reviewed by Barnett [6].

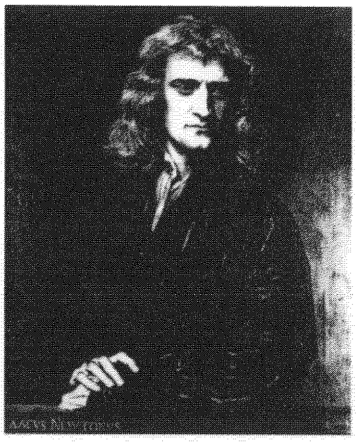
Newton was both experimentalist and observer. He laid down the mathematical principles through which nature operates. Substantial parts of both *Principia* and *Opticks* are devoted to reporting in detail the results of Newton's own experimental work. The contributions and influences of his work on fluid mechanics and aerodynamics are described by Hunsaker [7] and von Kármán [8], respectively. The following experiments on heat by Newton are noted here:

1. Experiments to determine the rate at which very hot bodies cool (Book III, Prop. XLI [4], pp. 521–522).
2. "A Scale of the Degrees of Heat" (1701) [1] describes experiments on the melting points of various metals.

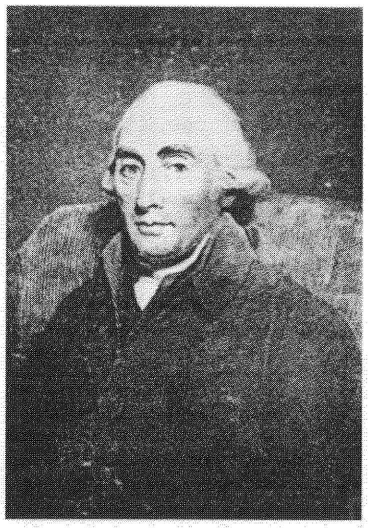
The development of thermometry before and after Newton is well reviewed by the following authors, among many others: Mach [9, 10], Bolton [11], Taylor [12], Barnett [13], and Middleton [14]. In Newton's time, experimental investigations and laboratories were not very common. Newton's laboratory was well equipped with crucibles, furnaces, various chemicals, and other facilities. He was engaged in making alloys of copper, antimony, iron, zinc, lead, tin, and bismuth. It is known that Newton was deeply interested in alchemical work throughout the thirty-odd years he was at Trinity College in Cambridge. He was also deeply concerned with the constitution and composition of matter. His notebooks recorded his sealed thermometer (made with oil) experiments on March 10, 1692 [15]. Several heat transfer devices (see Figures 3–5) relating to the development of thermometry before Newton's time are of historical interest. The mechanical contrivances shown in Figures 3 and 4 utilize the expansive and contractive properties of air, and represent the earliest thermal devices converting heat into work. The mechanical device shown in Figure 3 is also regarded as the origin of automatic control. In a treatise on pneumatics (third century B.C.), Philo described an intriguing experiment that was destined to have far-reaching implications for the development of the thermometer [6]. The apparatus shown in the inset of Figure 5 shows a large hollow glass globe sealed hermetically to one end of a long glass tube, the other end of which dipped into an open flask filled with water. Experiments in the sun and in shade demonstrated the movement of water caused by the expansive property of air. Some thermometers developed in the seventeenth and eighteenth centuries are shown in Figure 6.

Literature Review on Newton's Law of Cooling

Historical perspectives on Newton's law of cooling can be found in the classical treatises by Mach [9, 10], Glazebrook [16], Preston [17], Brush [18], and



Newton (1642-1727)



Black (1728-1799)

Fourier (1768-1830)

Carnot (1796-1832)

Planck (1858-1947)

Nusselt (1882-1957)

Figure 1 Six pioneers in heat transfer research for the period 1700 to 1920.

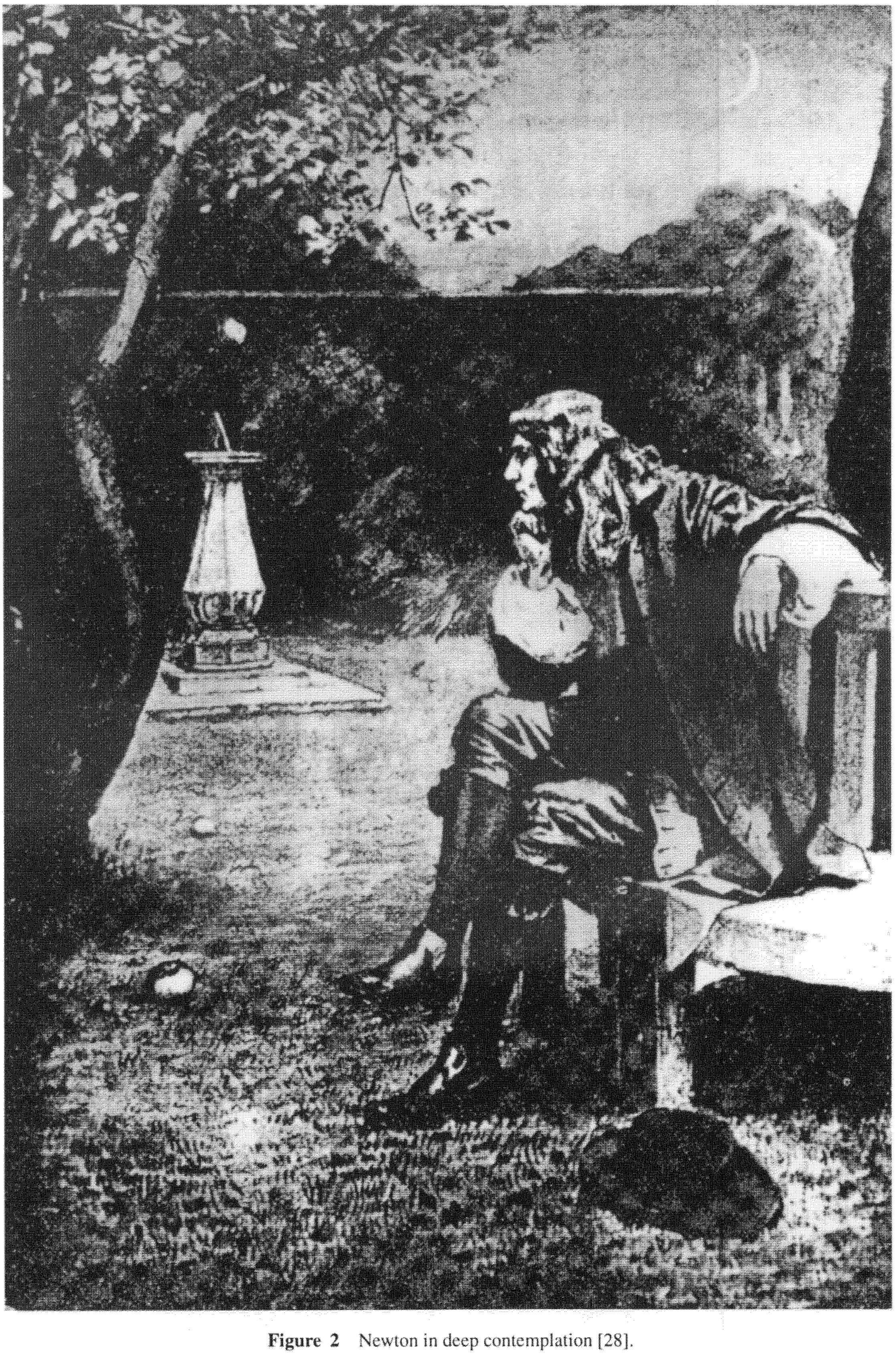


Figure 2 Newton in deep contemplation [28].

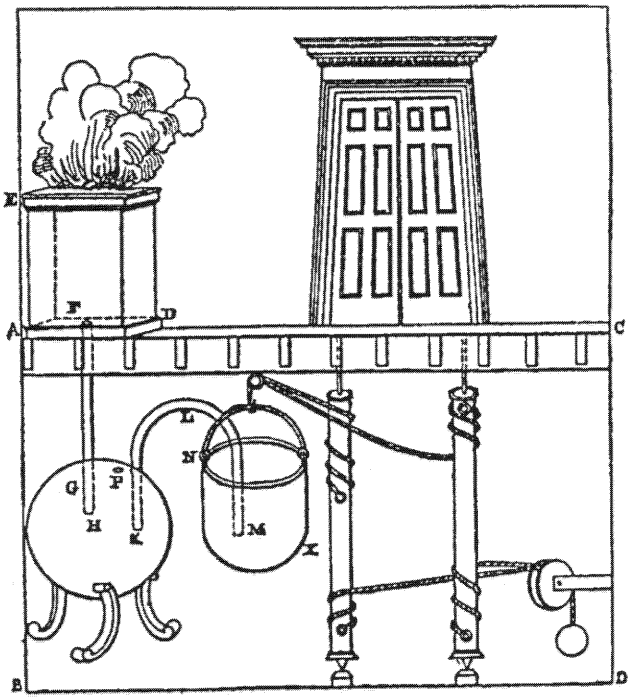


Figure 3 Hero's device for using heat from an altar fire to open temple doors (1680).

Truesdell [19]. The origins of Newton's law of cooling are apparently very important in the history of heat transfer. Ruffner [20] presents a careful analysis of the genesis of the law of cooling, emphasizing Newton's attempt to extend the existing temperature scales to higher temperatures, such as that of red-hot iron.

Grigull [3, 21] presents an analysis and interpretation of Newton's observed values for his temperature scale, and finds that Newton's results generally correspond quite well with the presently accepted temperature values as shown in Figure 7. Grigull [3] measured the

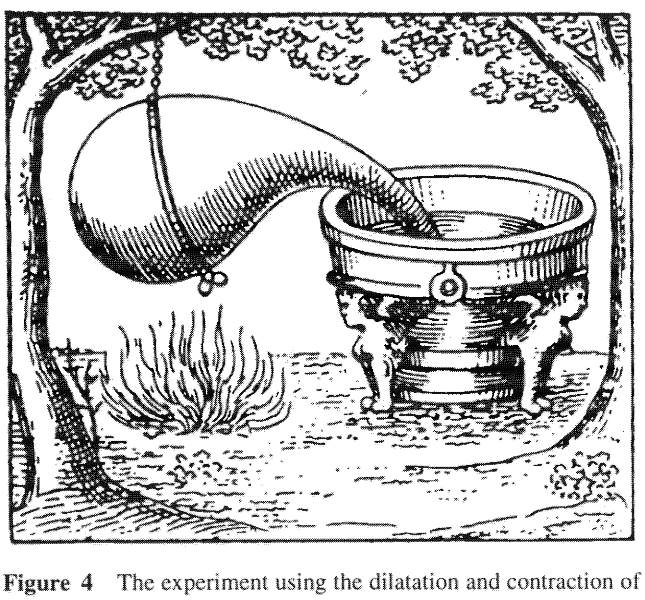


Figure 4 The experiment using the dilatation and contraction of air to raise water (1608).

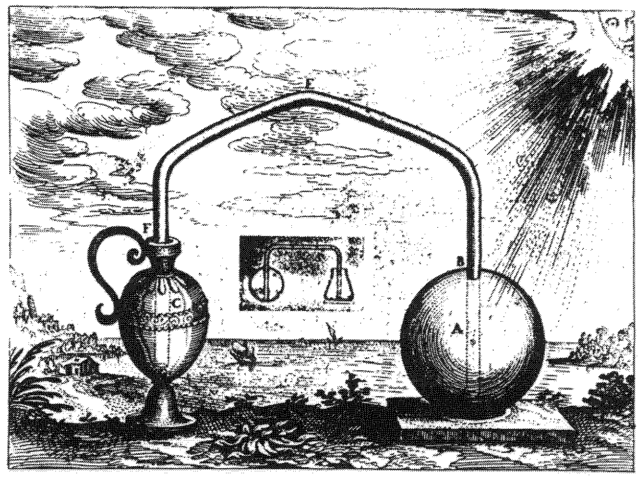


Figure 5 Fludd's figure of Philo's experiment (forerunner of the thermometer) [14].

expansion coefficients of linseed oil, which had been used in Newton's linseed oil thermometer, and found that the reproducible fixed points (melting and freezing points of various alloys) generally agreed quite well with the presently accepted temperature values, considering the possible errors in time measurements in Newton's era. In Figure 7, the fixed points are lettered B–D and the results of Grigull's analysis based on Newton's theory for the cooling of a red-hot iron are shown as a straight line without the effect of thermal radiation

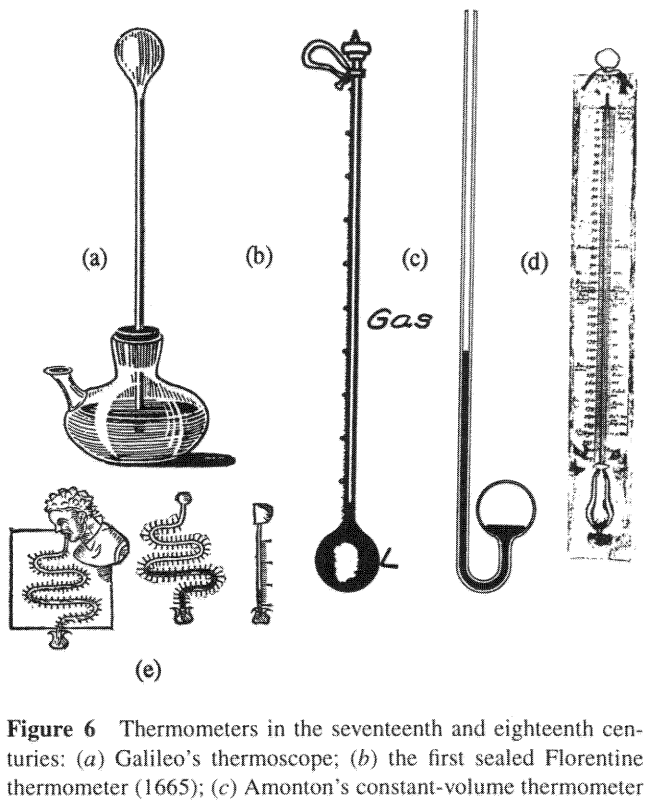


Figure 6 Thermometers in the seventeenth and eighteenth centuries: (*a*) Galileo's thermoscope; (*b*) the first sealed Florentine thermometer (1665); (*c*) Amonton's constant-volume thermometer (1702); (*d*) thermometer used by Celsius (1737); (*e*) the first clinical thermometers of Santorio (1612).

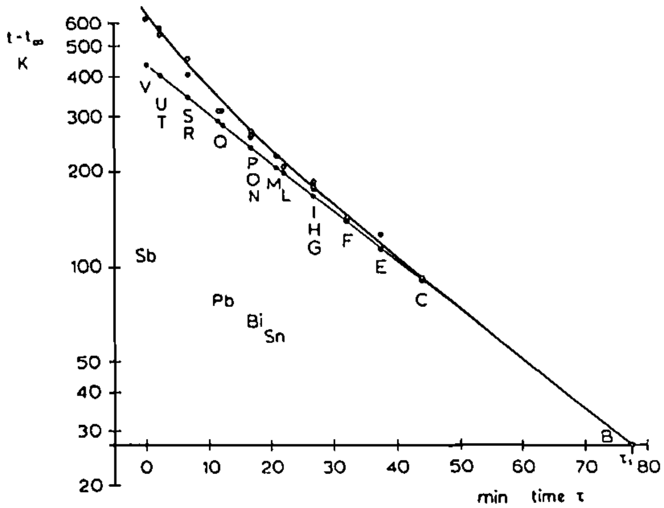


Figure 7 Newton's theory (cooling curve) and measured values in semilogarithmic presentation [3].

Table 1 Principal points of Newton's temperature scale

Degrees of heat	Equal parts of heat	
0	0	Heat of winter air when water begins to freeze
1	12	The greatest heat at the surface of the human body and that at which eggs are hatched.
2	24	Heat of melting wax
$2\frac{1}{2}$	34	The heat at which water boils violently
3	48	The lowest heat at which equal parts of tin and bismuth melt
4	96	The lowest heat at which lead melts
5	192	The heat of a small coal fire not urged by bellows
		The heat of a wood fire is from 200 to 210.

and as a curved line considering the thermal radiation effect (the real cooling curve for iron). It can be seen that Newton's measured values for the higher range of temperatures can also be reproduced satisfactorily [3]. Grigull's study is most informative and incisive, considering the historical significance of Newton's law of cooling in convective heat transfer.

Adiutori [22, 23] discussed the origins of the heat transfer coefficient and emphasized the important contributions of Fourier [24]. Bergles [25] noted the inaccuracy of Newton's law arising from internal temperature gradients, time-dependent heat transfer coefficient, and above all, neglect of the radiation effect. A brief account of subsequent developments in heat transfer after Newton was also given by Bergles.

Newton's Law of Cooling

In the literature, Newton's law of cooling is synonymous with the following statement: The rate of cooling of a warm body at any moment is proportional to the temperature difference between the body and its surrounding medium (air).

Newton's linseed oil thermometer had as fixed points the temperature of melting snow and that of the human body. The principal points of the temperature scale, from melting ice to a small coal fire, are given in Table 1. In this table, the first column represents the degrees of heat in arithmetic proportion (x) and the second column represents the degrees of heat in geometric proportion (y). Newton's scale of the degrees of heat for high temperatures is expressed in a logarithmic scale according to the formula

$$y = y_0 a^n = 12(2^{x-1}) \tag{1}$$

where x is the logarithmic temperature (degree of heat) and y is the arithmetic scale (equal parts of heat). Newton extrapolated widely to give the melting points of various alloys up to the temperature of a small coal fire (192° Newton). He obtained Eq. (1) by observation and reasoning, but he did not show his analysis.

The analysis is known as Newton's cooling problem and leads readily to the exponential form for the temperature drop. The exponential form of the temperature solution can be shown to be identical with Eq. (1). The essence of Newton's law of cooling (or Newton's cooling curve) can be expressed as

$$\frac{dT}{T} = \text{constant at any instant}$$

or

$$\frac{\Delta T}{T} = \text{constant per unit time} \tag{2}$$

Newton actually performed transient heat conduction experiments with turbulent forced-convection cooling, using a linseed oil thermometer and the fusion points of alloys and metals. Effectively, Newton obtained the transient temperature response curve for the cooling of red-hot iron. Newton's cooling curve is shown in Figure 8 [26]. Since the temperature of the red-hot iron is over 525°C, the thermal radiation effect is significant in the higher temperature range.

In one source (Frisinger [27]), Newton's linseed oil thermometer is described as 3 ft long with a bulb 2 in. in diameter. In Query 18 of Newton's *Opticks* [4], one finds the statement "two little thermometers." Thus, for the cooling experiment with hot iron, Newton's thermometer might have been smaller in size. Apparently, Newton's thermometer is similar to the thermometers of the Royal Society, 1663–1768. The linseed oil

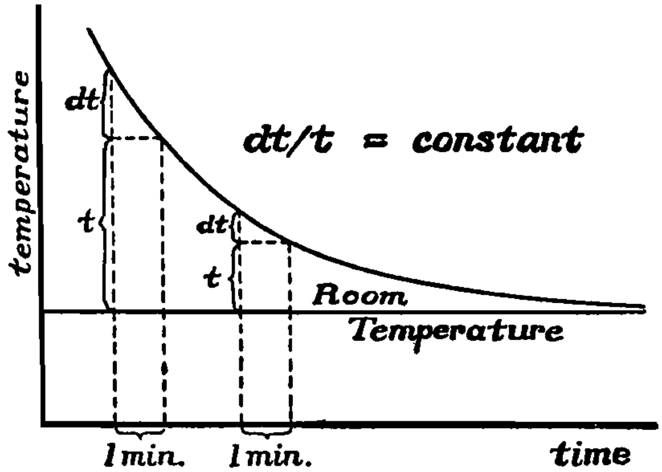


Figure 8 Newton's cooling curve [26].

thermometer experiment is an interesting example of the accuracy of Newton's observations and his considerable experimental skills. Examples of theoretical calculations based on Newton's law of cooling are also shown by Ruffner [20]. Newton notes that if the volume of the oil in the melting snow is 10,000 parts, it will be 10,256 at body heat and 10,705 at the boiling point of water. It is likely that some time elapsed before it was generally known that Newton had written the paper, although this was common knowledge in the 1740s, by which time there were better thermometers (Middleton [14]).

Newton reasoned that since, in equal times, equal quantities of air particles came in contact with the body, an equal number of air particles were heated by the body by an amount proportional to the "heat" of the body. Hence the "heat loss" of the body must be proportional to the "heat" of the body. But this loss was actually proportional to the readings of the linseed oil thermometer. Hence the "heat" of the body must be proportional to the readings of the thermometer (Barnett [13]). Apparently, the concepts of temperature and heat were not clearly differentiated, as yet, in Newton's time. Joseph Black finally distinguished between the quantity of heat and the intensity of heat or temperature, in the later part of the eighteenth century.

Boyle's thermometer (Florentine) had only one fixed point, namely, the temperature of melting ice. Boyle's statement, "at the beginning, very fast and afterwards, more slowly," indicates that the rate at which heat flows from one body to another decreases as the difference between their temperatures grows less (Newton's law of cooling); but apparently Boyle was not aware of this law [28]. It is of historical interest to observe that Boyle gave a qualitative demonstration of the principle known as Newton's law of cooling in his book, *Experiments Touching Cold*, in 1665.

From experimental observations on the rate of cooling of hot iron, Newton found by observation and reasoning that during equal intervals of time the same proportionate change in the excess of temperature took place. Newton determined this law in order to estimate high temperatures, such as that of a red-hot iron plate ("a large enough block of iron"), from observations on the time taken in cooling through known temperatures. Apparently Newton distinguished between forced and free convection, since he stated that "I placed the iron not in quiet air but in a uniformly blowing wind."

Newton did not present his analysis, but his statements (observations) can be represented by the following equation:

$$\log \frac{\Delta t}{(\Delta t)_0} = -\alpha\tau \tag{3}$$

where Δt is the excess temperature at time τ, and $(\Delta t)_0$ is the initial excess temperature.

By differentiating, one obtains

$$-\frac{d(\Delta t)}{d\tau} = \alpha(\Delta t) \tag{4}$$

This shows that the rate of temperature drop is proportional to the existing temperature excess. This equation contains the germ of the concept of heat transfer coefficient. One notes that the logarithm of the excess of temperature versus time is a straight line. In light of current knowledge, Newton's law is valid only for small excesses, such as the response of a thermometer with Δt = 20–30°C. The formulation of Newton's cooling problem clearly reveals that a time increase is equivalent to an increase of entropy.

Newton's enunciation of the cooling law shows a striking resemblance to his statement (*Principia*, Book II, Proposition 2, Theorem 2) that a moving body resisted in proportion to its velocity decelerates in proportion to its velocity. Thus, in Eq. (4), one may simply replace (Δt) by the velocity v. The analogy was noted by Cardwell [29]. Newton is also known to have experimented with the resistance of his body by moving around in a gale-force wind.

The distinction between quantity of heat and temperature was crucial to Black's experiments. Black, in his lectures (published in 1803, after his death) [30], gave a clear account of Newton's experiments and his law of cooling. Black's own experiments made use of the law of cooling, and Newton's dynamic method was the key to Black's calorimetry. Black used the concept of thermal equilibrium and conservation of heat, based on the caloric theory of heat, in temperature and heat measurements. Black's dynamic measurement of heat is based on the observation that the heat gained or lost should be proportional to the temperature and the time of heat flow. The influence of Newton is quite apparent. The following heat storage equation is credited to Black (1763):

$$Q = C\Delta t \tag{5}$$

where Δt is the difference between the initial and final temperatures. This equation is analogous to Hooke's law (1679) in elasticity:

$$F = K\Delta x \tag{6}$$

The similarity of the expressions is quite striking, but the physical processes are quite different.

FOURIER'S APPLICATIONS OF NEWTON'S LAW OF COOLING (1822) [24]

Fourier's derivation of the transient heat conduction equation was based on the concepts of heat capacity, thermal conductivity (internal conductivity), Fourier's law of heat conduction, and the heat balance (conservation of energy). Fourier's concept of an external conductivity (heat transfer coefficient) was apparently influenced by Newton's law of cooling. Biot [31] noted the proportionality between the heat transfer rate and the temperature gradient and also the distinction between the thermal conductivity and the coefficient in Newton's law of cooling.

It is convenient here to see Fourier's formulation of the boundary-value problem for the propagation of heat in solids with the associated convective boundary condition as

$$\frac{\partial t}{\partial \tau} = \alpha \nabla^2 t \tag{7}$$

$$-k\left(\frac{\partial t}{\partial n}\right)_w = h(t_w - t_\infty) \tag{8}$$

It is significant to note that Fourier effectively decoupled the conduction problem from the convection problem in his formulation by using the concept of the heat transfer coefficient. This procedure contributes to the ready identification of heat conduction as a mode of heat transfer and also to the maturity of heat conduction theory by the end of the nineteenth century.

Fourier also incorporated the concept of heat transfer coefficient (Newton's law of cooling) at the solid surface in the heat conduction equation for a heated prism or thin plate in free air (fin problem) as

$$A\frac{\partial \theta}{\partial \tau} = \frac{kA}{\rho C_p}\frac{\partial^2 \theta}{\partial x^2} - \frac{hP}{\rho C_p}\theta \tag{9}$$

Two limiting cases are of special interest here.

For the steady-state case, $\partial\theta/\partial\tau = 0$ and one has

$$\frac{d^2\theta}{dx^2} = \frac{hP}{kA}\theta \tag{10}$$

When the thermal conductivity $k = \infty$, the conduction term $\partial^2\theta/\partial x^2 = 0$ (no temperature gradient), and the problem reduces to Newton's cooling problem:

$$\rho C_p V\frac{dt}{d\tau} = -hA(t - t_\infty) \tag{11}$$

For Newton's cooling problem, the initial condition is $\tau = 0$, $t = t_0$. Equation (9) is usually treated as a fin problem in elementary heat transfer texts, for various boundary conditions at one end. For the special cases $x = 0$, $\theta = \theta_0$ and $x = \infty$, $\theta = 0$, one obtains the solution as

$$\theta = \theta_0 e^{-mx} \tag{12}$$

where $m = (hP/kA)^{1/2}$. Apparently, this problem is similar to Newton's cooling problem, and the distance x corresponds to time τ. One also sees the geometric progression of the temperature excesses. The solution also agrees with Lambert's logarithmic law (1779) (Truesdell [19]). After the work of Newton, Amontons [10, 19], and Lambert, Biot [31] also verified Lambert's logarithmic law.

Fourier also confirmed Newton's law of cooling experimentally. For Newton's cooling problem, Fourier [24] obtained the following equation:

$$\frac{hS}{\rho C_p V} = \frac{\log t_1 - \log t_2}{\tau_2 - \tau_1} \tag{13}$$

The quantity $hS/\rho C_p V$ or h can be determined from the experiment.

Fourier's analysis [24] of the propagation of heat in a solid sphere (Chapter 5) is noteworthy. After obtaining the exact solution for the case with uniform initial temperature, Fourier considers the limiting case when the Biot number, $\mathrm{Bi} = hr_0/k$ ($r_0 =$ radius of a sphere), is very small. After carrying out order-of-magnitude analysis for the terms in the exact series solution, Fourier deduces the following asymptotic solution:

$$t = \exp\left(-\frac{3h\tau}{\rho C_p r_0}\right) = \exp(-3\,\mathrm{Bi\,Fo}) \tag{14}$$

where Fo is the Fourier number. This result corresponds to the analysis based on Newton's law of cooling, and is considered to be most remarkable, reflecting Fourier's considerable insight.

The significance of the Biot number was clearly recognized by Fourier (1822).

The extent of Fourier's indebtedness to Newton in his analytical theory of heat is of considerable historical interest. The details can be found in Fourier [24], Grattan-Guinness [32], and Herivel [33]. It is significant to conclude that the exact solutions for Newton's cooling problem (1701) of a hot body, considering the internal temperature gradients for various geometric shapes, were obtained by Fourier.

Fourier [24, p. 282] notes that the analysis on the cooling of a sphere of small dimension also applies to the heat transfer problem of a thermometer surrounded by fluid.

The classical method of solution for Eq. (7), using the separation of variables, leads immediately to

$$\frac{dt}{t} = -\alpha P^2\,d\tau \qquad \text{or} \qquad t(\tau) = Ae^{-\alpha P^2 \tau} \tag{15}$$

where P^2 = separation constant. Also, by replacing the term $\partial^2 t/\partial x^2$ in the conduction equation by a finite-difference form, one sees readily that the time rate of local temperature change is proportional to the existing average temperature difference; this is clearly analogous to Newton's law of cooling. It is seen that the exponential term involving time in the analytical solution of the transient heat conduction problem represents Newton's legacy. The determination of the temperature distribution by Fourier series, is Fourier's basic contribution.

It is of historical interest to note that the basic energy equation for moving fluids was derived by Fourier in 1820, before the appearance of the Navier-Stokes equation [24].

After reading an earlier version of this article [34], Prof. E. R. G. Eckert wrote the following comment: "Did Newton devise the relation $q = h\Delta t$ for the conditions of his experiments to establish a temperature scale only, or did he claim a more general validity for it? He obviously was aware of the restriction to forced convection and your formulation 'now universally known as Newton's Law' seems to point to it. In other words, was the relation above considered only by others after him a general law (and called Newton's Law)?"

Equation (8) clearly shows that Fourier transformed Newton's cooling law into the relationship between wall heat flux, q_w, and temperature difference, Δt, with h = constant. Thus, Fourier should be credited with the relation, $q_w = h\Delta t$, defining the heat transfer coefficient using Newton's law of cooling. Apparently, Black had already mentioned "Newton's law" in his lectures (1803), and the usage continued with Biot [31], Fourier [24], and others after them. It is of interest to note that Fourier used the term "heat transfer" [24]. In Fourier's work, Biot number appears as thermal boundary condition. The three limiting cases, (1) Bi $\rightarrow \infty$ (constant wall temperature), (2) Bi $\rightarrow$ 0 (constant wall heat flux), (3) Bi = 0 (perfect insulation), are noted here. The distinction between Bi $\rightarrow$ 0 and Bi = 0 is considered to be significant.

THE INFLUENCE OF NEWTON'S COOLING LAW ON THE DEVELOPMENT OF RADIATION HEAT TRANSFER IN THE NINETEENTH CENTURY

The problem of the transfer of heat by radiation was first investigated by Newton (*Opticks*, 1704). Although he favored the corpuscular view of the nature of light, he maintained that radiation of heat was due to a vibration in ether.

A comprehensive review of the influences of Newton's law of cooling on the development of radiation heat transfer, including the three modes of heat transfer (conduction, convection, and radiation), in the nineteenth century was given by Brush [18]. The following aspects of the history are considered: (1) heat and radiation in the nineteenth century; (2) radiant heat and the decline of the caloric theory; (3) the Dulong-Petit law of cooling; (4) the temperature of the sun; (5) the Stefan-Boltzmann law; and (6) the three modes of heat transfer.

In reviewing the measurement of extreme temperatures, Callendar [35, 36] presented two informative figures (see Figures 9 and 10) showing the predictions for thermal radiation from a black body (temperature range 0–1200°C) and the temperature of the sun by extrapolation using formulas proposed by several investigators. The limitation of Newton's law of cooling in radiation heat transfer is clearly seen in Figures 9 and 10. The curves in Figure 9 illustrate some of the typical formulas based on the law of radiation or the results of experiments. Figure 10 represents the results of extrapolation as applied to deducing the probable temperature of the sun [35].

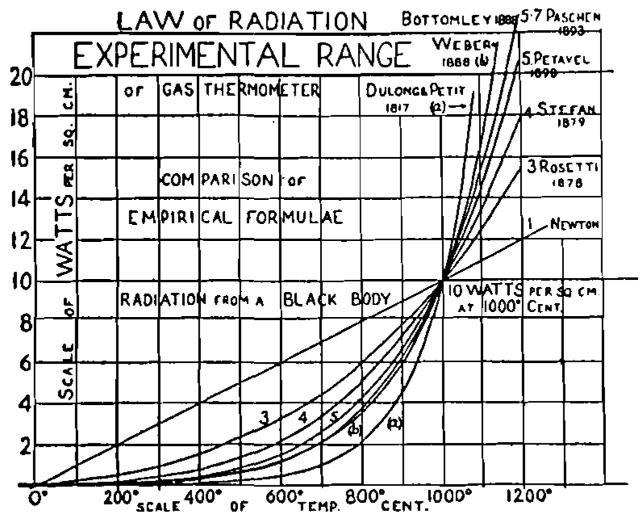


Figure 9 Formulas for radiation, experimental range [35].

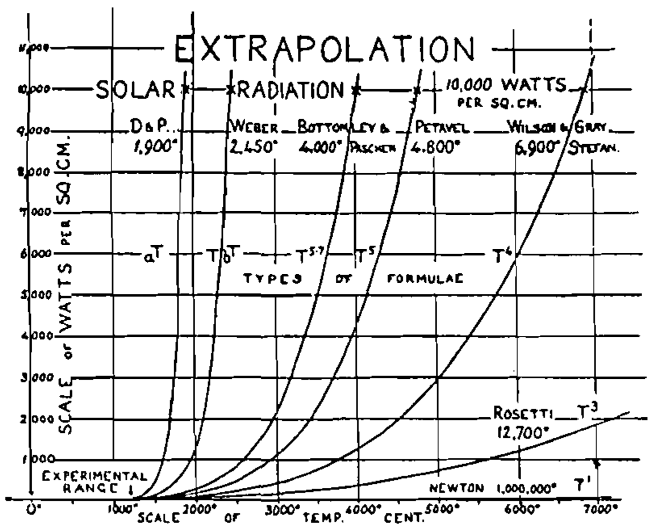


Figure 10 Temperature of the sun by extrapolation [35].

THE DEVELOPMENT AND EXTENSION OF THE CONCEPT OF HEAT TRANSFER COEFFICIENT

Newton's cooling law represents a linear rate equation for the rate of heat loss from a hot body to its ambient air based on the temperature difference. Fourier [24] incorporated the concept of the heat transfer coefficient as the convective boundary condition in his formulation of the mathematical theory of heat conduction, to circumvent the complex convection and radiation problems at the body surface. Thus, the parameter Biot number also appears as a physical parameter.

In an excellent review of forced and natural convection [16], the equations for the rate of heat loss from various basic solid bodies are presented, but the heat transfer coefficient defined by $q_w = h\Delta t$ is not identified clearly. However, the heat transfer correlation equations shown already reveal the modern dimensionless variable in the form of the Nusselt number. By around 1920, Boussinesq's theory for forced convection and the principle of similitude developed by Rayleigh (1915) were already available [16].

The decisive step in the application of the concept of the heat transfer coefficient in forced- and natural-convection heat transfer occurred with the appearance of the classical paper by Nusselt in 1915 [37]. This paper, showing an application of similarity analysis based on the governing differential equations for forced- and natural-convection problems, exerted a considerable influence on subsequent developments in convective heat transfer theory. Henceforth, the Nusselt number has been in common use for correlating the heat transfer results for various convective thermal phenomena.

Although the method of similarity had been used by Reynolds (1883) and by von Helmholtz (1873), Nusselt extended the method, establishing a correlating principle for convective heat transfer. The dimensionless correlation equations, using Nusselt number, for convective heat transfer were previously available (see, for example, Gröber's famous heat transfer text [38]).

As noted, Newton's experimental work on thermometry in 1701 was concerned with the turbulent forced-convection heat transfer problem between a red-hot iron and a forced uniform air current. It is of special interest to observe that the practical approach to the determination of the heat transfer coefficient in internal and external turbulent flows was first proposed by Reynolds [39] in the form of the Reynolds analogy, and improved subsequently by Prandtl [40], Taylor [41], and von Kármán [42].

Incidentally, historical remarks by Prandtl [43] reveal vividly the same train of thought that went through the minds of Newton, Reynolds, and Prandtl. Prandtl's exposition of heat transfer in moving fluids in his famous "Essential of Fluid Dynamics" [43] represents a classic review of convective heat transfer.

One notes that all the convective heat transfer problems, including phase-change heat transfer, can be classified using the relationship between the wall heat flux, q_w, and the characteristic temperature difference, Δt, in the form $q_w \approx (\Delta t)^n$, with n depending on the particular thermal phenomenon. It is clear that Newton's law is valid only for forced convection with constant physical properties.

The applications of Newton's law of cooling to Fourier's heat conduction theory by Schlünder [44–46] represents an extension of the concept of the heat transfer coefficient in convection heat transfer to the heat conduction problem. By using the concept of the heat transfer coefficient in the heat conduction problem, Newton's cooling problem is found to be equivalent to determining the expression of the mean temperature of solid bodies (sphere, slab, cylinder, cube, prism) as a function of the time elapsed [44–46]. Schlünder's method can be readily applied to a class of forced-convection problems by observing the analogy between Fourier's transient heat conduction problem and a class of forced-convection problems with plug flow [47].

The heat transfer coefficient based on the logarithmic mean temperature difference has a theoretical basis in the expression for the total heat transfer rate for Newton's cooling problem [47]. The concept of overall heat transfer coefficient and NTU (number of transfer units) in heat exchanger applications can be regarded as an extension of the concept of the heat transfer coefficient.

Newton's cooling problem is a lumped-parameter method, which has been applied to various analogous physical phenomena. The applications include: (1) chemical process calculations, (2) error estimates in temperature measurement and transient experimental techniques for surface heat flux rates, (3) thermal anemometry, (4) heat transfer enhancement, (5) heat regulation in physiology (wind-chill factor), and (6) applications to the design of heat exchangers. The examples of applications are too numerous to describe here.

It is remarkable to observe that Lorenz (1881) investigated the heat loss due to natural convection from a heated vertical surface freely exposed to air, and found that heat loss is proportional to $(\Delta t)^{5/4}$, where Δt is the temperature difference between the surface and the air. Prandtl [43] notes that Lorenz's paper is the first paper on free convection and the first paper on the boundary layer. Boussinesq's analysis (1901) of cooling of a hot body by a stream of fluid (laminar flow) is also noted here. A brief chronology relating to the influences of Newton's law of cooling on heat transfer is shown in Table 2 for reference. Note that a comprehensive table of the chronology of heat transfer, covering the period 1690 to 1902, is presented by Dalby [48]. O'Sullivan [49] presented the extension of Newton's formulation to the cases of Dulong-Petit cooling, Stefan cooling, and calorimetric experiments.

Table 2 Chronology related to Newton's law of cooling

1593	Galileo, thermoscope (air thermometer)
1643	Torricelli's experiment on vacuum
1665	Boyle, "experiment touching cold," a qualitative demonstration of the principle later known as Newton's law of cooling
1687	Newton, *Principia*
1701	Newton, "A Scale of the Degrees of Heat," the paper containing Newton's law of cooling (exponential law of cooling), quantity of heat
1702	Amontons, air thermometer, the concept of absolute zero degrees
1704	Newton, *Opticks*
1724	Fahrenheit, temperature scale
1740	Martine, the first person to realize the limitation of Newton's law of cooling
1742	Celsius, temperature scale
1760	(1762) Black, specific heat, latent heat
1803	Black, lectures on the elements of chemistry, contains an account of Newton's law of cooling
1804	Biot, the proportionality between heat transfer rate and temperature gradient, the distinction between the thermal conductivity and the coefficient in Newton's law of cooling (Biot number)
1807	Fourier, the law of heat conduction, derivation of the transient heat conduction equation, application of Newton's law of cooling to the convective boundary condition and to the fin problem
1820	Fourier, derivation of the energy equation for moving fluids
1822	Fourier, *Analytical Theory of Heat*
1822	(1845) Navier-Stokes equations
1824	Carnot, the motive power of heat
1848	Kelvin, concept of absolute temperature
1874	Reynolds analogy for turbulent heat transfer
1875	Grashof, equation for heat exchanger
1879	(1884) Stefan-Boltzmann law for black-body radiation
1881	Lorenz, analytical theory for natural convection
1883	(1885) Graetz problem
1894	Reynolds equations for turbulent flow
1897	Stanton number
1900	Planck, laws of black-body radiation
1901	(1905) Boussinesq, the first analytical solution for cooling of a heated body by a stream of fluid (laminar flow, Newton's cooling problem)
1904	Prandtl, boundary-layer theory
1910	Prandtl analogy for turbulent heat transfer; Nusselt, thermal entrance region problem in tube (Graetz problem)
1915	Nusselt, basic law of heat transfer (Nusselt number)
1916	Rayleigh, application of similitude to forced convection
1916	Taylor analogy for turbulent heat transfer
1921	Pohlhausen, laminar forced convection on a flat plate (Blasius flow)
1939	von Kármán analogy for turbulent heat transfer

CONCLUDING REMARKS

One observes a striking resemblance between Newton's statement of the law of cooling and that of a moving object subjected to a frictional resistance proportional to its velocity. The two problems are now known to be completely analogous. Also, a stream of water is said to have suggested to Fourier the first distinct picture of heat flow. Carnot observed the analogy between a fall of temperature and a fall of water. The works of Newton, Fourier, and Carnot are also independent of the nature of heat. Since heat flow is invisible or cannot be observed directly, the conceptions of the basic principles in the theory of heat must be based on analogy with visible phenomena.

Newton's pioneering paper enunciating his law of cooling appeared in 1701. Fourier's analytical theory of heat (1822) and Carnot's *Reflections on the Motive Power of Heat* (1824) were completed during the first quarter of the nineteenth century. Planck's quantum theory of thermal radiation (1900) and Prandtl's boundary-layer theory (1904) [50] appeared early in the twentieth century. It is evident that the foundations of heat transfer theory were practically completed by the end of the nineteenth century.

The nature of heat transfer research in this century is quite different from that in the nineteenth century. Apparently, the pioneers in heat transfer early in this century played important roles in the transition from the science of heat to applications in thermal engineering. A substantial catalog of heat transfer results (basic and applied) has been accumulated in the twentieth century. The accomplishments in the first half of this century are well documented in the classical treatises by Jakob (1949, 1957) and McAdams (1954). The accomplishments in the second half of this century are contained in review articles, books, and journals, and remain to be critically assessed in the future. It is hoped that a historical review on heat transfer in the twentieth century, comparable to that of Mach (1896), may be forthcoming in the near future. A more detailed study of Newton's influence on heat transfer in the light of present heat transfer developments would be of considerable historical interest.

NOMENCLATURE

A	cross-sectional area of a prism, surface area, constant
C	heat capacity
C_p	specific heat at constant pressure
F	force
h	constant heat transfer coefficient
k	thermal conductivity
K	spring constant
P	perimeter of a cross section
q_w	wall heat flux
Q	heat quantity
S	external surface of a body
t, t_w, t_∞	temperature, wall temperature, ambient temperature
V	volume of a body
x	coordinate
α	thermal diffusivity, proportionality constant
$\Delta t, (\Delta t)_0$	temperature difference, initial temperature difference
Δx	elongation
θ	temperature difference, $(t - t_\infty)$
ρ	density
τ	time

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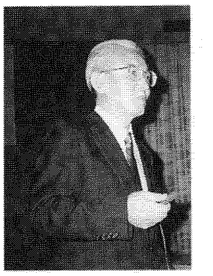

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