



HISTORY OF HEAT TRANSFER

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ENHANCEMENT OF CONVECTIVE HEAT TRANSFER: NEWTON'S LEGACY PURSUED

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ABSTRACT

A review of the background of "Newton's Law of Cooling" leads to the conclusion that it is appropriate to credit Newton with the concept of the convective heat transfer coefficient. Furthermore, because his early experiments with heat were alluded to in the *Principia*, the 300th anniversary of this legendary volume should honor him as a pioneer in heat transfer as well as in solid and fluid mechanics. Newton's legacy also includes a realization of factors that improve the heat transfer coefficient, thus providing the earliest basis for the now rapidly growing science of heat transfer enhancement. Some early history and the present status of this "Second Generation Heat Transfer Technology" are briefly reviewed.

NEWTON AND CONVECTIVE HEAT TRANSFER

Isaac Newton is widely credited with the following statement of the convective heat transfer coefficient:

$$q = hA (T_{\text{sur}} - T_{\text{surr}}) \quad (1)$$

Where q is the rate of heat transfer, h the heat transfer coefficient, A the surface area, T_{sur} the surface temperature, and T_{surr} the temperature of the surroundings. The usual reference is a brief paper read at a meeting in 1701 and published that year (Newton, 1701).¹ While the originator of this attribution is not clear, it is sufficient to note that McAdams (1942) made such a statement and subsequent authors have followed suit up to the present day (e.g., Janna, 1986). There are difficulties in accepting the historical accuracy of this statement because nowhere in the paper is specifically mentioned a constant of proportionality between heat flux and temperature difference. Indeed, there is sharp criticism of those who would identify Newton with equation (1), e.g., Adiatori (1974).

¹It is of more than passing interest that this work was published anonymously. This was a characteristic of 17th century scientific communication; however, there was rarely any doubt who wrote an article.

Newton was concerned with the calorimetry needed to fix high and low points on the "Newton Temperature Scale." His description of the procedure and the mathematics was entirely verbal – in the circuitous style of the times:

"This table was constructed by means of the thermometer and red-hot iron. By the thermometer were found all the degrees of heat, down to that which melted tin; and by the hot iron were discovered all the other degrees; for the heat which hot iron, in a determinate time, communicates to cold bodies near it, that is, the heat which the iron loses in a certain time, is as the whole heat of the iron; and therefore, if equal times of cooling be taken, the degrees of heat will be in geometrical proportion, and therefore easily found by the tables of logarithms

. . . . there was heated a pretty thick piece of iron red-hot, which was taken out of the fire with a pair of pincers, which were also red-hot, and laid in a cold place, where the wind blew continually upon it, and putting on it particles of several metals, and other fusible bodies, the time of its cooling was marked, till all the particles were hardened, and the heat of the iron was equal to the heat of the human body; then supposing that the excess of the degrees of the heat of the iron, and the particles above the heat of the atmosphere, found by the thermometer, were in geometrical progression, when the times are in arithmetical progression, the several degrees of heat were discovered; the iron was laid not in a calm air, but in a wind that blew uniformly upon it, that the air heated by the iron might be always carried off by the wind, and the cold air succeed it alternately; for thus equal parts of air were heated in equal times, and received a degree of heat proportional to the heat of the iron"

Interpreting this somewhat, Newton placed samples of pure metals and alloys on a red-hot, thick piece of iron and noted the times at which the samples solidified as the iron cooled in an air stream. The ratio of the temperature differences was then obtained simply by assuming that this ratio was in geometrical progression when the times were in arithmetic progression. As pointed out in the excellent study by Ruffner (1960), however, there is no explicit evidence in any of Newton's writings to explain the logical basis of the procedure. Newton did not state it in the mathematical form of his "fluxions" or calculus. On the other hand, geometrical progressions were widely used by Newton and his contemporaries because they described a variety of physical phenomena. For example, Book II, Proposition II, Theorem II of the Principia (Newton, 1687) proposes such a geometrical law for the velocity decay in an object moving by its inertia only in a viscous medium. (Indeed, the idea of a Newtonian fluid stems from the Principia, Book II, Section IX.)

In any event, the mathematics was developed subsequently. Briefly, the instantaneous heat flux is assumed proportional to the time rate of change of the iron temperature (lumped parameter) and the temperature difference between the iron and the air:

$$\frac{q}{A} \sim \frac{dT}{dt} \sim T - T_{\infty} \quad (2)$$

Although equation (1) is often referred to as "Newton's Law of Cooling", equation (2) is considered by most to be the proper mathematical statement of the law. Assuming uniform and equal temperatures of the samples and the iron as well as an invariant

constant of proportionality, the temperature for a particular fixed point on the temperature scale is given by

$$\ln \frac{T_{FP} - T_{\infty}}{T_{body} - T_{\infty}} = \frac{t_{body}}{t_{FP}} \quad (3)$$

where t_{FP} is the time required to cool to T_{FP} and t_{body} is the time required to cool to body temperature, T_{body} , one of the original fixed points on Newton's temperature scale. A linseed-oil-in-glass thermometer was used by Newton to determine T_{body} and the air temperature, T_{∞} , for the experiments. A typical result was that 57 degrees Newton is the freezing point of a mixture of one part lead and one part bismuth. The inaccuracies in equation (3) arise from internal temperature gradients, temperature-dependent convective heat transfer coefficients, and, above all, neglect of radiation.

It is of interest to inquire whether the heat transfer problem was mentioned prior to 1701 or even prior to Newton's laboratory notebooks of 1692-93. Sure enough, in Principia, Book III, Proposition XLI, Problem XXI (Newton, 1687), the "heat of boiling water" and "heat of red-hot iron" are mentioned. It is very likely that Newton had at that time formulated his basic concepts of heat transfer. Thus, the 300th anniversary celebration of the Principia, which is still continuing, should honor Newton as a pioneer in heat transfer as well as in solid (e.g., Petroski, 1987) and fluid mechanics.

To summarize this Newtonian historical prelude, it seems reasonable to conclude that Newton's convective cooling conjecture was established by the time the Principia was published in 1687. In effect, the Principia represents the first publication of his ideas. He elevated the hypothesis to a basic principle in the 1690's as a result of careful experimentation and measurement. The work was finally presented at a meeting and published in 1701. While Newton did not specifically mention a quantity that resembles the convective heat transfer coefficient, the implicit recognition of the role of the coefficient as a constant of proportionality in equation (2) seems to be adequate justification to give Newton credit for the heat transfer coefficient. He is thus a heat transfer pioneer as well as a mechanics pioneer, and the Principia should be celebrated for both reasons.

SUBSEQUENT DEVELOPMENTS

Equation (2) became known as "Newton's Law of Cooling", certainly by the time of Fourier (1822). In any event, equation (1), with h designated the "external conductivity", was used by Fourier as a boundary condition for the heat conduction equation. Fourier also commented on the necessity to consider radiation as well as convection and briefly discussed factors that influence both forced and free convection. It is primarily the radiation that caused deviations from the "law" and, in fact, led to many efforts to discredit the law during the 1700's. An elegant assessment in modern terms of the effect of radiation was given by Grigull (1978, 1984).

Succeeding work was directed toward the accumulation of values of the heat transfer coefficient for a wide range of circumstances. See, for example, Mollier (1897). The heat transfer coefficient continued to be referred to as "conductivity" through much of the 1800's (Joule, 1861). By the late 1900's, the present terminology seems to have been widely adopted. Nusselt's 1909 pioneering work to correlate heat transfer coefficients is the basis for the modern science of convective heat transfer. It must be pointed out, however that it took several more years before the grouping hd/k , now known as the Nusselt number, was specifically mentioned by Nusselt (1915).

The art and science of convective heat transfer has grown rapidly in this century. We now have empirical, analytical, and numerical correlations providing the heat transfer

that enhance the convection. It is thus appropriate that the ongoing tricentennial celebration of Newton's Principia recognizes Newton's pioneering work in heat transfer as well as his contributions to solid and fluid mechanics. There is no doubt that the next 50 years of the ASME Heat Transfer Division will continue to be characterized by a strong emphasis on enhanced heat transfer.

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