Origins of the Heat Transfer Coefficient

Though Newton has long been recognized in physics and heat transfer texts, an examination of evidence in the literature reveals a new answer to the question, Who should be credited with the *h* concept?

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Heat transfer texts generally credit Isaac Newton with the concept of the heat transfer coefficient (*h*). Those texts which give a specific reference cite his article "A Scale of the Degrees of Heat" published in 1701 in the *Philosophical Transactions of the Royal Society of London*. The article was published anonymously and in Latin. An English translation was published in 1749 in the third edition of the *Philosophical Transactions Abridg'd* by Henry Jones.

In physics texts and in heat transfer texts, the 1701 article by Newton is cited as the source for what is usually called "Newton's law of cooling." Surprisingly, this law appears in three different forms:

$$d\Delta T/dt \ \alpha \ - \Delta T \qquad (1)$$

$$q \ \alpha \ \Delta T \qquad (2)$$

$$q/A = h \ \Delta T \qquad (3)$$

The evidence in the literature clearly indicates that Fourier should be credited with several fundamental concepts of modern heat transfer. Fourier's credits include: the concepts of heat flux, heat transfer coefficient, and thermal conductivity, as well as the solution of boundary condition problems by matching the internal and external flux at the boundary.

It is nothing short of amazing that, almost 200 years after its publication, Fourier's treatise on heat transfer is conceptually quite modern. At the same time, the evidence in the literature clearly indicates that:

- Equation 1 is the *only* form of Newton's law of cooling described in his 1701 article.
- Equation 1 is the only form of Newton's law of cooling that should be credited to Newton.
- Newton had no understanding of heat flux. Therefore, he could not possibly have conceived the heat transfer coefficient concept.
- Joseph Black bridged the gap between Equations 1 and 2 by clearly distinguishing between heat and temperature, and by his experimental results, which demonstrated that specific heat depends little on temperature.
- Fourier should be credited with several of the fundamental concepts of modern heat transfer, including the heat transfer coefficient and Equation 3.

Newton's Law

Physics texts generally give Newton's law of cooling in the form of Equation 1 and/or Equation 2. Heat transfer texts generally give the law in the form of Equation 3 and thereby credit Newton with the *h* concept.

Within the framework of 20th-century thermal science, Equations 1, 2, and 3 are extremely simple. Their seeming simplicity results because they are based on mathematical and thermal concepts that are very familiar and have been used for many decades. But in an absolute sense, Equation 2 is conceptually much more difficult than Equation 1. Note that:

- Equation 1 requires an understanding of only one thermal concept—the intensive parameter named "temperature" (*T*).
- Equation 2 requires an understanding of and a clear distinction between two thermal concepts—the intensive parameter "temperature" and the extensive parameter "heat" (*q*). Moreover, "heat" is a much more difficult concept than temperature because an understanding of heat can be gained only through the intellect, whereas an understanding of temperature is gained readily and universally through the sense of touch.
- Equation 3 requires an understanding of four thermal concepts: temperature, heat, heat flux (*q/A*), and heat transfer coefficient. Since the concepts of heat flux and heat transfer coefficient build on the concept of heat, they are conceptually even more difficult than the con-

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PART II.

Containing the

PHYSIOLOGICAL PAPERS.

CHAP. I.

Physiology. Meteorology. Pneumatics.

A Scale of the Degrees of Heat, by ... n.270. p.824.

0		I. THE Heat of Winter Air, when Water begins to freeze. This Heat is known by rightly placing the Thermometer in Snow pressed together, at what Time it begins to thaw.
0, 1, 2.		The Heat of Winter Air.
2, 3, 4.		The Heat of the Air in Spring and Autumn.
4, 5, 6.		The Heat of the Air in Summer.
6.		The Heat of the Air at Noon, about the Month of *July*.
12.	1	The greatest Heat that the Thermometer receives by the Contact of a Human Body. This Heat is much the same as that of a Bird sitting upon her Eggs.
$14\frac{3}{11}$	$1\frac{1}{4}$	The Heat of a Bath, which is almost the greatest that any one can endure long, with his Hand agitated and immersed in it. The same almost is the Heat of Blood just let out.
17	$1\frac{1}{2}$	The greatest Heat of a Bath that any one can endure long, his Hand being immersed and at rest in it.
$20\frac{2}{11}$	$1\frac{3}{4}$	The Heat of a Bath in which Wax swimming and melting, by moving about grows hard and loses its Transparency.
24	2	The Heat of a Bath in which Wax swimming grows liquid by the Heat, and is preserved in continual Flux without Ebullition.
$28\frac{6}{11}$	$2\frac{1}{4}$	The intermediate Heat between the Degrees in which the Wax melts and the Water boils.
34	$2\frac{1}{2}$	The Heat by which Water boils violently, and a Mixture of two Parts of Lead, of three Parts of Pewter, and

Heat source. An English translation of Newton's 1701 Latin "A Scale of the Degrees of Heat" was published in 1749 in the third edition of the *Philosophical Transactions Abridg'd* by Henry Jones.

cept of heat.

The point of this is to indicate that, with regard to thermal concepts, Equations 1, 2, and 3 are vastly different. Therefore, the extent of Newton's contribution to thermal science depends strongly on which of these equations reflects the substance of his 1701 article.

An examination of the literature reveals the true extent of Newton's contribution to thermal science. On the basis of evidence in the literature, I will also answer the question, Who should actually be credited with the h concept?

Even a casual reading of Newton's 1701 article reveals that its subject is temperature rather than heat, even though the word temperature never appears in the article, and the word heat appears almost a hundred times. The main thrust of the article is Newton's proposed temperature scale based on 0°, defined by "The Heat of Winter Air, when Water begins to freeze," and 12°, defined by "The greatest Heat that the Thermometer received by the Contact of a Human Body."

The first part of the article is a table which contains the "heats" Newton measured and reported using his proposed scale of the "degrees of heat." The second part of the article describes the experiment he designed and performed, and the rationale behind the data reduction.

"Heats" in the range 0° to 72° were obtained with a "linseed oyl" thermometer "by supposing the Heat of the Oyl proportional to its Rarefaction" (i.e., inversely proportional to its density). "Heats" in the range 12° to 192° were determined by placing small quantities of substances which would melt on a "piece of red hot iron" which Newton intentionally put "in a cold Place, where the Wind blew constantly." The data were "the Times of Cooling, till all the Particles grow stiff and lost their Fluidity" (i.e., the data were the elapsed times from the beginning of the cool-down to the solidification of each substance which had been placed on the iron).

Newton reduced the "Times of Cooling" data to temperatures by assuming that the "Excesses of the Heat of the Iron. . . are in Geometrical Progression when the Times are in Arithmetical Progression."

Citing Texts

Heat transfer texts generally credit Newton with the h concept, citing his 1701 paper. William Giedt, in *Engineering Heat Transfer* (Princeton: Van Nostrand, 1957) gives the equation as:

$q = hA(T_{surface} - T_{fluid})$

M. Jakob, in *Heat Transfer* (New York: John Wiley, 1949) gives a similar equation and cites the 1701 paper.

Many heat transfer texts credit Newton with the h concept, but cite no specific reference. Two examples are J.P. Holman, in *Heat Transfer* (5th ed. New York: McGraw-Hill, 1981), and E. Eckert and R. Drake, Jr., in *Analysis of Heat and Mass Transfer* (New York: McGraw-Hill, 1972).

Understanding Heat

Newton described his "law of cooling" in the following passages:

> . . . the Heat which the iron loses in a given time, is as the whole Heat of the Iron. Therefore, if the Times of cooling are taken equal, the Heats will be in a Geometrical Ratio, and therefore are easily found by a Table of Logarithms.
>
> . . . the Excesses of the Heat of the Iron and the rigid Particles above the Heat of the Atmosphere found by the Thermometer, are in Geometrical Progression when the Times are in Arithmetical Progression. . . .

In order to understand these passages, it is essential to know what Newton and his colleagues intended by the word "heat," i.e., by the Latin word "calor" which Newton used in the original manuscript. Since Newton does not define "heat," its meaning must be obtained from the context in which it is used in the article. Newton states:

- 0 degrees is "the Heat of Winter Air, when Water begins to freeze."
- 6 degrees is "the heat of the air at noon."
- "The Heat of boiling water is almost three times greater than the heat of the human body."
- "If the times of cooling are taken equal, the heats will be in a geometrical ratio."

From its context in the article, it is apparent that "heat" has the singular meaning of warmth or hotness or temperature. It is equally apparent that "heat" has nothing to do with heat in the modern, scientific sense, that is, an extensive thermal parameter that describes a quantity of energy.

To Newton and his colleagues, the word "heat" meant the intensive thermal parameter now called temperature. Many decades after Newton's article, the word "heat" ceased to mean temperature to the scientist. But to the lay person, the word "heat" continued to mean temperature. James Clerk Maxwell, in his *Theory of Heat*, discussed the ambivalent character of the word:

> We have nothing to do with the word heat as an abstract term signifying the property of hot things, and when we might say a certain heat, as the heat of new milk, we shall always use the more scientific word temperature of new milk.

Note that the word heat has the same meaning to the 20th-century lay person that it had to Newton and his colleagues. That lay meaning is temperature, as evidenced by the definition of heat in *Webster's Third New International Dictionary, Unabridged* (Springfield: Merriam, 1968): "The state of a body or matter that is perceived as opposed to cold and is characterized by elevation of temperature: a condition of being hot; warmth;–hotness (the iron lost its heat in contact with the cold ground)."

Since the word "heat" meant temperature to Newton, the analytical expressions of Newton's words quoted earlier are:

$$d(T_{iron} - T_{atm})/dt \ \alpha - (T_{iron} - T_{atm}) \quad (4)$$

$$(T_{iron} - T_{atm}) = (T_{iron} - T_{atm})_{t=0} \ e^{-\lambda t} \quad (5)$$

Equations 4 and 5 are the analytical expression of the "law of cooling" described by Newton in 1701.

In Newton's article, the word "heat" means the intensive thermal parameter that is now called temperature. Therefore, there can be no doubt that the modern, scientific expression of the law of cooling described by Newton is as follows: the temperature which a hot object loses in a given time is proportional to the temperature difference between the object and the ambient.

And there can be no doubt that the analytic expression of the law of cooling described by Newton is given by Equation 1, 4, or 5 and *not* by Equation 2 or 3.

Modern Concept

Newton and his colleagues had only a limited and qualitative understanding of an extensive thermal parameter and did not draw a clear distinction between intensive and extensive thermal parameters. In fact, they used the same word for both parameters.

Notice that in his 1701 article, Newton used "heat" to mean an intensive thermal parameter (i.e., temperature). In the following passage from Query 18 of Newton's *Opticks* (1706), he uses "heat" to mean an extensive thermal parameter:

> [Suppose a vacuum bottle containing a thermometer] be carried out of a cold place into a warm one. . . . Is not the Heat of the warm room convey'd through the vacuum by the vibrations

A Scale of the Degrees of Heat.

		and of five Parts of Biſmuth grows ſtiff in cooling. Water begins to boil by a Heat of 33 Parts, and in boiling conceives a Heat of more than $34\frac{1}{2}$ Parts. But Iron with a Heat of 35 or 36 Parts ceaſes to excite an Ebullition, when hot Water is dropt upon it; and of 37 Parts, when cold Water does the ſame.
$40\frac{4}{11}$	$2\frac{3}{4}$	The leaſt Heat by which a Mixture of one Part Lead, of four Parts Pewter, and of five Parts Biſmuth, grows hot and melts, and is preſerved in a continual Flux.
48	3	The leaſt Heat by which a Mixture of equal Parts of Pewter and Biſmuth melts. This Mixture cools and coagulates by a Heat of 47 Degrees.
57	$3\frac{1}{4}$	A Heat by which a Mixture of two Parts of Pewter, and one Part of Biſmuth is melted, as alſo a Mixture of three Parts of Pewter, and two Parts of Lead. But a Mixture of five Parts of Pewter, and of two Parts of Biſmuth, cools and grows ſtiff with this Heat. And a Mixture of equal Parts of Lead and Biſmuth does the ſame.
68	$3\frac{1}{2}$	The leaſt Heat by which a Mixture of one Part of Biſmuth, and eight Parts of Pewter is melted. Pewter alone is melted with a Heat of 72 Parts, and cools and grows ſtiff by a Heat of 70 Parts.
81	$3\frac{3}{4}$	The Heat by which Biſmuth is melted, as alſo a Mixture of four Parts of Lead, and one Part of Pewter. But a Mixture of five Parts of Lead, and one Part of Pewter, grows ſtiff when melted, and cools in this Heat.
96	4	The leaſt Heat by which Lead is melted. Lead grows hot and melts in a Heat of 96 or 97 Parts, and cools and grows ſtiff in a Heat of 95 Parts.
114	$4\frac{1}{4}$	The Heat by which Bodies heated in the Fire by cooling quite leave off to ſhine in the Darkneſs of the Night, and again by growing hot begin to ſhine in the ſame Darkneſs, but with a very faint Light which can hardly be perceived. In this Heat a Mixture of equal Parts of Pewter and Regulus Martis will melt; but a Mixture of ſeven Parts of Biſmuth, and four Parts of the ſame Regulus Martis, will cool and grow ſtiff.
136	$4\frac{1}{2}$	The Heat by which Bodies heated in the Fire grow red hot, but not ſo in the Twilight. By this Heat a Mixture of two Parts of Regulus Martis, and of one Part of Biſmuth, as alſo a Mixture of five Parts of Regulus Martis, and one Part of Pewter, by cooling grows ſtiff. The Regulus by itſelf grows ſtiff with a Heat of 146 Degrees.

of a much subtler medium than air, which after the air was drawn out remained in the vacuum?

It is generally agreed that the first clear distinction between heat and temperature was made by Joseph Black in the middle of the 18th century. The *Encyclopedia Americana* (1984) states:

> Until the middle of the 18th century little or no distinction was made between heat and temperature. About that time Joseph Black. . . clearly distinguished between quantity of heat and intensity of heat, as temperature was designated. He noted that the amount of heat required to raise the temperature of a unit mass of substance through one degree is nearly constant. This he called heat capacity.

The first clear distinction between heat and temperature was made in 1760. Since this distinction is essential to Equations 2 and 3, it follows that these equations cannot possibly be described in Newton's article of 1701.

Conceptually, there is an immense chasm between Equations 1 and 2. This chasm could not be bridged until a clear distinction was made between heat and temperature, and the experimental evidence was obtained which would demonstrate that specific heat is little affected by temperature. Black contributed both the understanding required to make a clear distinction and the experimental evidence.

It is only because of Black's tremendous contribution that Equation 2 is readily obtained from Equation 1. Thus, the real credit for Equation 2 belongs to Black, not Newton.

Heat Flux

Equation 3 defines the heat transfer coefficient to be the ratio of heat flux to ΔT. J. Herivel, in *Joseph Fourier* (Oxford: Clarendon Press, 1975), discusses the origin of the heat flux concept:

> [The concept of heat flux] must be regarded as [Fourier's] most critically important and original single insight into the physical nature of the conduction of heat in solid bodies. . . . Fourier's contemporaries [Laplace, Biot, and Poisson] found it excessively difficult either to understand or to accept this concept.
>
> . . . This is surely another example of one of those apparently simple, almost trivial, concepts in theoretical physics which nevertheless seem to require for their formulation the intervention of a Galileo or a Newton.

In the early part of the 19th century, Fourier conceived the heat flux concept—a gigantic conceptual leap, as evidenced by the prolonged, stubborn resistance from the most eminent physicists in the world. Since heat flux is an essential part of the h concept, it follows that h and Equation 3 cannot possibly be described in Newton's 1701 article.

Heat Transfer Coefficient

Conceptually, the principal difference between Equations 2 and 3 is that Equation 3 requires an understanding of the heat transfer coefficient concept and Equation 2 does not. Equation 2 states that the heat flow rate is proportional to the temperature difference. Equation 3 seems to state that the heat flux is proportional to temperature difference, and assigns the symbol *(h)* to what appears to be the constant of proportionality.

Fourier intended Equation 3 to indicate that, during convective heat transfer, heat flux and temperature difference were generally proportional. However, it has long been recognized that heat flux is *not* generally proportional to ΔT.

Rather than discard Equation 3 because it does not describe convective thermal behavior in a general way, the modern practice is to retain Equation 3 and interpret it to mean simply that h is defined to be the ratio of heat flux to temperature difference.

In *The New Heat Transfer,* I pursue the alternate path, abandoning Equation 3 and formulating a new thermal science that contains no heat transfer coefficients.

Since Fourier conceived the heat flux concept, it seems likely that he should also have conceived the heat transfer coefficient concept, since the latter is a relatively small extension of the former. Fourier (1822) states that he did, in fact, conceive the heat transfer coefficient concept, as well as the thermal conductivity concept:

> . . . the effects of the propagation of heat depend in the case of every solid substance, on three elementary qualities, which are, its capacity for heat, its own conducibility, and the exterior conducibility. . . . [The capacity for heat] is exactly defined, and physicists have for a long time known several methods of determining its value. *It is not the same with the two others;* their effects have often been observed, but there is but one exact theory which can fairly distinguish, define, and measure them with precision.
>
> We have taken as the measure of the external conducibility of a solid body a coefficient h, which denotes the quantity of heat which would pass, in a definite time (a minute), from the surface of this body, into atmospheric air, supposing that the surface had a definite extent (a square metre), that the constant temperature of the body was 1, and that of the air 0, and that the heated surface was exposed to a current of air of a given invariable velocity. This value of h is determined by observation.
>
> We have taken this coefficient K, which enters into the (above) equation, to be the measure of the specific conducibility of each substance. . . .

Fourier's claim to the h concept is validated by Herivel who compares Fourier's treatment of surface heat transfer with that of his well-known contemporaries:

> Since Fourier's boundary condition does no more than tie together the flow of heat up to, but just beneath, the surface with the actual flow at the surface, it is surprising to find that it was one of the aspects of the 1807 memoir criticized by Biot and Laplace [and by Poisson]. . . .
>
> Laplace's [and presumably Biot's] views on the question are given at the end of the section on heat in Laplace's 1809 paper on diffraction. There he assumes that the surface of a heated body rapidly reaches that of the surrounding medium, and that a law is then quickly established governing the rise of temperature within the body up to a certain maximum value U. The loss of heat is then proportional to U.

It is important to note that this view expressed by Laplace in 1809 and endorsed by Biot considers that temperature is *continuous* at solid/fluid boundaries, that is, that the surface of any object immersed in any fluid rapidly reaches the fluid temperature. This also means that the heat transfer coefficient at any surface in any fluid is essentially infinite. (I. Grattan-Guinness's *Joseph Fourier 1768–1830* states that Poisson also shared this view.)

Laplace, Biot, and Poisson were physicists of the first rank. Since they had no understanding of convective heat transfer during the same time period in which Fourier's understanding was quite complete, Fourier's claim to the heat transfer coefficient concept is undoubtedly accurate. ■

For Further Reading

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