WHAT'S WRONG WITH h?

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ABSTRACT

For almost 200 years, the heat transfer coefficient (h) concept has been the foundation of convective heat transfer. Unfortunately, this concept suffers from two flaws:

- h is unnecessary
- h is undesirable

h cannot be necessary because h is not a parameter of Nature--it is a contrived parameter--it is found only in the intellect. h is in fact nothing more than a shorthand way of writing the dimensional group $(q/\Delta T)$.

h is undesirable because it artificially complicates the solution of every problem it touches. How? By making it identically impossible to separate the variables we most want to separate--q and ΔT. The h concept requires that problems be solved without separating the variables, and this lack of separation artificially complicates the solution of the problem. If the problem involves simple, proportional behavior, then the artificial complexity contributed by h is minimal. But if the problem involves nonlinear thermal behavior--if it involves free convection, or boiling, or condensation--then the h concept adds so much artificial complexity that many problems of practical import are virtually impossible to solve. These same problems are transformed into simple exercises by simply keeping q and ΔT separate--and abandoning h.

The text illustrates how to solve heat transfer problems without h.

NOMENCLATURE

Note that the symbols define the parameter and the units. For example, the symbol q denotes heat flux in Btu/hr ft2. Therefore, the expression "q = 14000" means that the heat flux is 14000 Btu/hr ft2. Thus no units appear in the text, since they are defined by the symbols.

D	diameter in feet
h	heat transfer coefficient in Btu/hr ft2 °F
k	thermal conductivity in Btu/hr ft °F
Nu	Nusselt number
Pr	Prandtl number
q	heat flux in Btu/hr ft2
Re	Reynolds number
t	thickness in feet
ΔT	temperature difference across an interface in °F
U	overall heat transfer coefficient in Btu/hr ft2 °F
x	mathematical parameter--analog of ΔT
y	mathematical parameter--analog of q

Subscripts

i	refers to interface or ith item
w	" " wall

SUMMARY

The concept of the heat transfer coefficient (h) has been a cornerstone of heat transfer science throughout the 19th and 20th centuries. But the h concept is flawed in a mathematical way, and because of this flaw,

- h complicates the solution of every problem it touches.
- Every problem that can be solved with h can be solved better without it.

The flaw in the h concept may be seen by noting that:

- By definition, h is the dimensional group $(q/\Delta T)$.
- The mathematical analogs of q, ΔT, and h are y, x, and (y/x).
- In mathematics, we strive to separate y and x because separating them greatly simplifies the solution of the problem. Separation requires that we eliminate all groups which contain both y and x--such as the group (y/x).
- In heat transfer, it is impossible to separate q and ΔT if the problem solution is based on h. This is because h is actually the group $(q/\Delta T)$.
- The necessity to solve heat transfer problems without separating q and ΔT complicates the solution of every problem.

The artificial complexity which results from using h can be eliminated only by abandoning h--by simply refusing to divide q by ΔT. Only when h is abandoned can the solution of heat transfer problems be based on separated variables and therefore be as simple as possible.

When the solution of heat transfer problems is based on separated variables, the simple expression

$$\Delta T_{total} = \Sigma \Delta T_i \qquad (1)$$

replaces heat transfer coefficient expressions such as

$$U = \frac{1}{1/h_1 + 1/h_2 + t/k} \qquad (2)$$

The solution of heat transfer problems based on Eq 1 is illustrated below.

BACKGROUND

Heat transfer texts generally allege that the heat transfer coefficient concept was conceived by Newton. (See Refs 3 to 11.) Those texts which give a specific reference generally cite Newton's "A Scale of the Degrees of Heat" published in 1701. (See Ref 2. The first page of Newton's article is reproduced in Appendix A.)

Surprisingly, Newton's article contains no understanding of the h concept. Moreover, it contains no understanding of the modern view of heat as an <u>ex</u>tensive property. Note in Appendix A that Newton repeatedly uses the word "heat" to denote an <u>in</u>tensive property.

Since Newton did not conceive of h, we must look elsewhere to determine who should actually be credited with the h concept. In his <u>Analytical Theory of Heat</u> (1) published in 1822, Fourier credits himself with the h concept. A comparison of Fourier's work with that of his colleagues Biot (12) and Laplace (13) leaves little doubt that Fourier is telling the truth. (Ref 14 describes the development of the major heat transfer concepts from Newton's time to the present.)

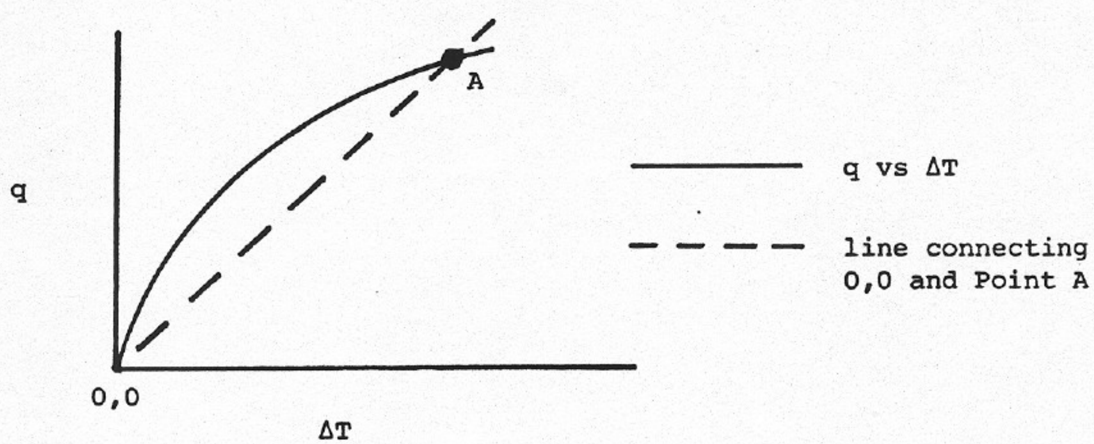
Ever since Fourier conceived of h, it has been a cornerstone of heat transfer science. However, it must be noted that Fourier viewed h as the proportionality constant between q and ΔT. Later, when it became known that q was <u>not</u> generally proportional to ΔT, it became necessary to redefine h. As a result of this redefinition, h ceased to be a constant and became a variable--it became the variable $(q/\Delta T)$.

WHAT EXACTLY IS h?

The following observations about h are accurate and do not contain the slightest exaggeration:

- h is an INVENTED variable.
- h does NOT exist in Nature.
- h exists ONLY in the intellect.
- h is merely a shorthand way of writing the dimensional group $(q/\Delta T)$.
- The ONLY way to "measure" h is to measure q and ΔT and then divide q by ΔT.
- When we say that h is 10, we are really saying that, at some unspecified ΔT, the ratio of q to ΔT is 10.
- When dealing with nonlinear heat transfer such as free convection or boiling, h transforms problems which involve only TWO variables (q and ΔT) into problems involving THREE variables (q, ΔT, and h). This superfluous third variable adds nothing but complexity and confusion to what would otherwise be simple exercises.

The exact nature of h is also revealed by its graphical equivalent. On the sketch below, the slope of the dashed line is the graphical equivalent of h at Point A.



Note that in mathematics, we have NO USE for the slope of the dashed line because the slope of this line cannot effectively be used for anything. And yet the slope of this line has been the foundation for convective heat transfer for almost 200 years!

WHAT EXACTLY IS h USED FOR?

In configurations involving one or several solid/fluid interfaces, h is used to determine q given ΔT, and ΔT given q.

THE THERMAL BEHAVIOR OF SOLID/FLUID INTERFACES

The thermal behavior of solid/fluid interfaces may be grouped as follows:

<u>Proportional</u> $q \propto \Delta T$ Example: forced convection

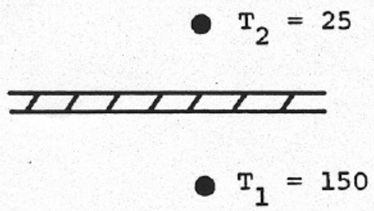
<u>Moderately nonlinear</u> $q \propto \Delta T^n$ where $1<n<2$
Example: free convection

<u>Highly nonlinear</u> includes regions where $\frac{dq}{d\Delta T} < 0$
Example: boiling

SOLVING PROPORTIONAL BEHAVIOR PROBLEMS WITH AND WITHOUT h

The example below illustrates the solution of heat transfer problems involving proportional thermal behavior. The example illustrates the solution based on h and the solution based on abandoning h.

PROBLEM 1 What is q in the system shown below?



SOLUTION WITH h

$h_1 = 15$

$h_2 = 7$

$t_w = .05$

$k_w = 1.6$

$$U = \frac{1}{1/h_1 + 1/h_2 + t_w/k_w}$$

$$U = \frac{1}{1/15 + 1/7 + .05/1.6}$$

$U = 4.15$

$q = U\,\Delta T = 4.15(150-25)$

$q = 519$

SOLUTION WITHOUT h

$q_1 = 15\,\Delta T_1$

$q_2 = 7\,\Delta T_2$

$t_w = .05$

$q_w = 1.6\,\Delta T_w/t_w$

$\Delta T_{total} = \Delta T_1 + \Delta T_2 + \Delta T_w$

$(150-25) = q/15 + q/7 + .05q/1.6$

$q = 519$

THE SIGNIFICANCE OF PROBLEM 1

Note the following in Problem 1:

- In the solution with h, the thermal behavior of the interfaces and the wall are described in terms of the coefficients h and k.

- In the solution without h, the thermal behavior of the interfaces and the wall are described in terms of their thermal behavior. (Note that the phrase "thermal behavior" logically refers to the functional relationship between heat flux and thermal driving force.)

- The solution with h is based on Eq 2. The solution without h is based on Eq 1.

- Eq 1 is so simple as to be truly obvious. And while Eq 2 is not difficult in an absolute sense, by no stretch of the imagination can it be described as "obvious".

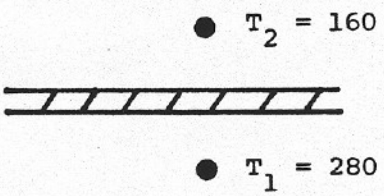
- The solution with h is roundabout in that the problem asks for the value of q and we actually solve for the value of U. In the solution without h, the problem asks for the value of q and we solve for the value of q.

- Both solutions give the same answer. The only difference is methodology. The methodology inherent in the solution without h is simpler, more direct, and more logical.

SOLVING HIGHLY NONLINEAR PROBLEMS WITH AND WITHOUT h

The example below illustrates the solution of heat transfer problems involving highly nonlinear thermal behavior. Problems of this type can be solved with or without h. However, the correct solution with h would be extremely difficult and time consuming. Therefore, the "with h" solution is given only in outline form, and the detailed solution is left for the reader.

PROBLEM 2 What steady-state values of q are possible in the system shown below?



SOLUTION WITH h

$h_1 = 900$

h_2 = see Figure 2

$k_w = 10$

$t_w = .00455$

It is possible to correctly solve this problem using h and Eq 2. A great deal of iteration is required, the details of which are left to the interested reader. (It should be noted that this problem has never been correctly solved with conventional heat transfer science based on h.)

SOLUTION WITHOUT h

$q_1 = 900\ \Delta T_1$

q_2 = see Figure 1

$q_w = 10\ \Delta T_w/t_w$

$t_w = .00455$

$$\Delta T_{total} = \Delta T_1 + \Delta T_2 + \Delta T_w$$

$$(280 - 160) = q/900 + \Delta T_2 + q(.00455)/10$$

$$q = 76600 - 639\ \Delta T_2 \qquad (3)$$

Eq 3 describes the flow of heat into interface 2, whereas Fig 1 describes the flow of heat out of interface 2. Plotting both heat flows on the same graph results in Fig 3. Since the two heat flows are equal only at the intersections in Fig 3, we conclude that q can be any of the following: 14000, 42000, or 58000. However, the intersection at 42000 is thermally unstable (see Ref 15), and thus the steady-state value of q is either 14000 or 58000.

THE SIGNIFICANCE OF PROBLEM 2

Note the following in Problem 2:

- The solution without h is extremely simple.

- The solution with h is extremely difficult.

- Problem 2 has great practical significance because it closely resembles a boiler in a very general way. To illustrate: interface #1 resembles a condensing vapor heat source; interface #2 resembles a boiling fluid (note that Fig 1 resembles the so-called pool boiling curve); the wall resembles the plate in a simple pool boiler (or a differential element of a tube in a forced convection boiler).

- There are two possible steady-state values of q.

- The boiler is unable to operate stably at the middle intersection in Fig 3 because Eq 4, the generic criterion for thermal stability (15), is not satisfied at interface 2.

$$\frac{dq_{in}}{dT_i} < \frac{dq_{out}}{dT_i} \qquad (4)$$

- That Problem 2 has never been correctly solved with h is best demonstrated by the following statement taken from conventional heat transfer:

  > With condensing vapor as the heat source on one side of a wall, any point on the entire pool boiling curve can be reached under stable conditions.

  This conventional view holds that, in a boiler of this type, the temperature of the condensing vapor uniquely determines the heat flux and therefore assures stable operation. As demonstrated in the without h solution, this conventional view simply does not agree with the behavior of real world equipment.

CONCLUSIONS

Problems 1 and 2 cover the complete spectrum of heat transfer problems conventionally solved using h. Both of these problems are better solved without h than with h, thus supporting the following conclusions:

- h should be abandoned because it is unnecessary and undesirable.

- Every problem that can be solved with h can be solved more simply without it.

- Researchers should correlate heat transfer data with q and ΔT separate and explicit because this is the form required for design/analysis when h is abandoned. (Note that pool boiling data are already reported in this desirable form. However, the reason for this is not because it is required for design/analysis. The reason is that noted by W. H. McAdams at an ASME meeting in 1947 where he made the following comment on the h vs ΔT pool boiling curves of Farber and Scorah (17):

  Because of the possibility of error in temperature measurement, it would be safer to plot heat-flux density versus temperature, rather than coefficient versus temperature in order to isolate any possible error in the abscissa.)

- Designers/analysts should design/analyze using q and ΔT and Eq 1 (rather than q and ΔT and h and Eq 2) because this is the simplest possible way.

- Educators should teach heat transfer design/analysis using q and ΔT and Eq 1.

- Correlations already written in terms of h should be transformed so that q and ΔT are separate and explicit. (This transformation is quite simple. It requires merely that h be replaced by $q/\Delta T$ and that q and ΔT be separated. For example, Eq 4 is readily transformed to Eq 5.)

$$Nu = .023\ Re^{.8}\ Pr^{.4} \tag{4}$$

$$q = .023\ (k/D)\ Re^{.8}\ Pr^{.4}\ \Delta T \tag{5}$$

Heat transfer science without h is described in detail in Ref 16.

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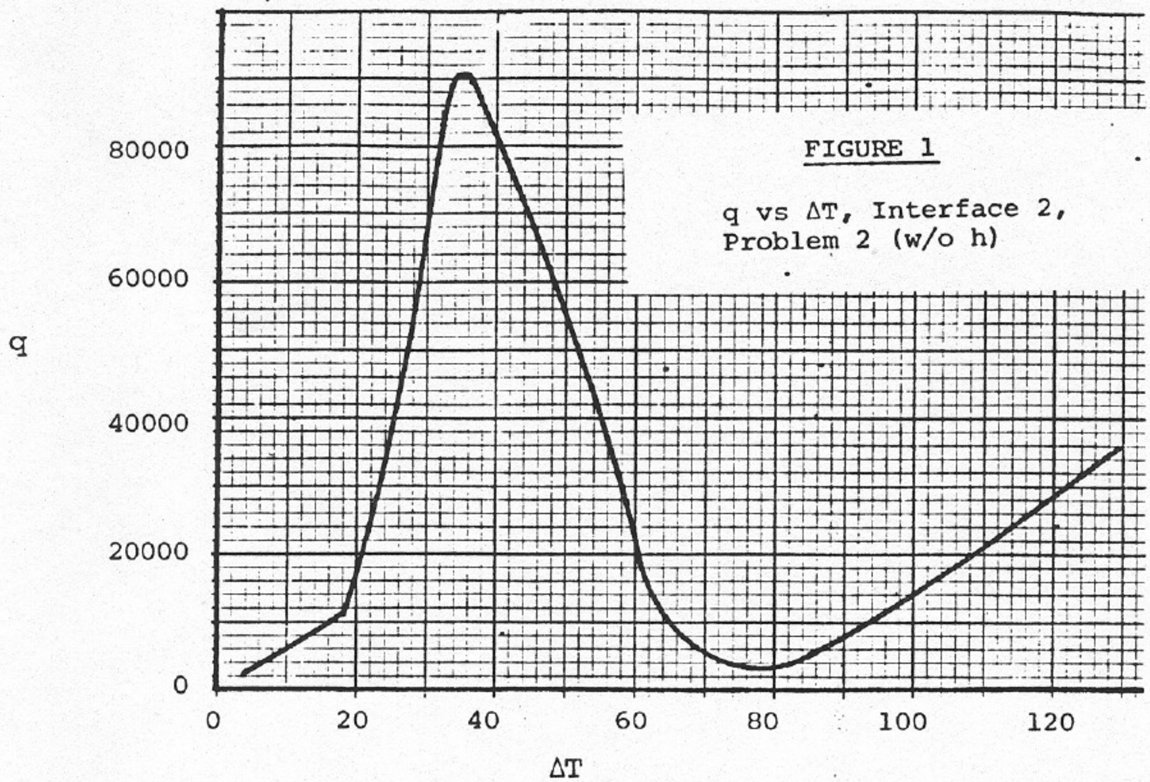

FIGURE 1

q vs ΔT, Interface 2,
Problem 2 (w/o h)

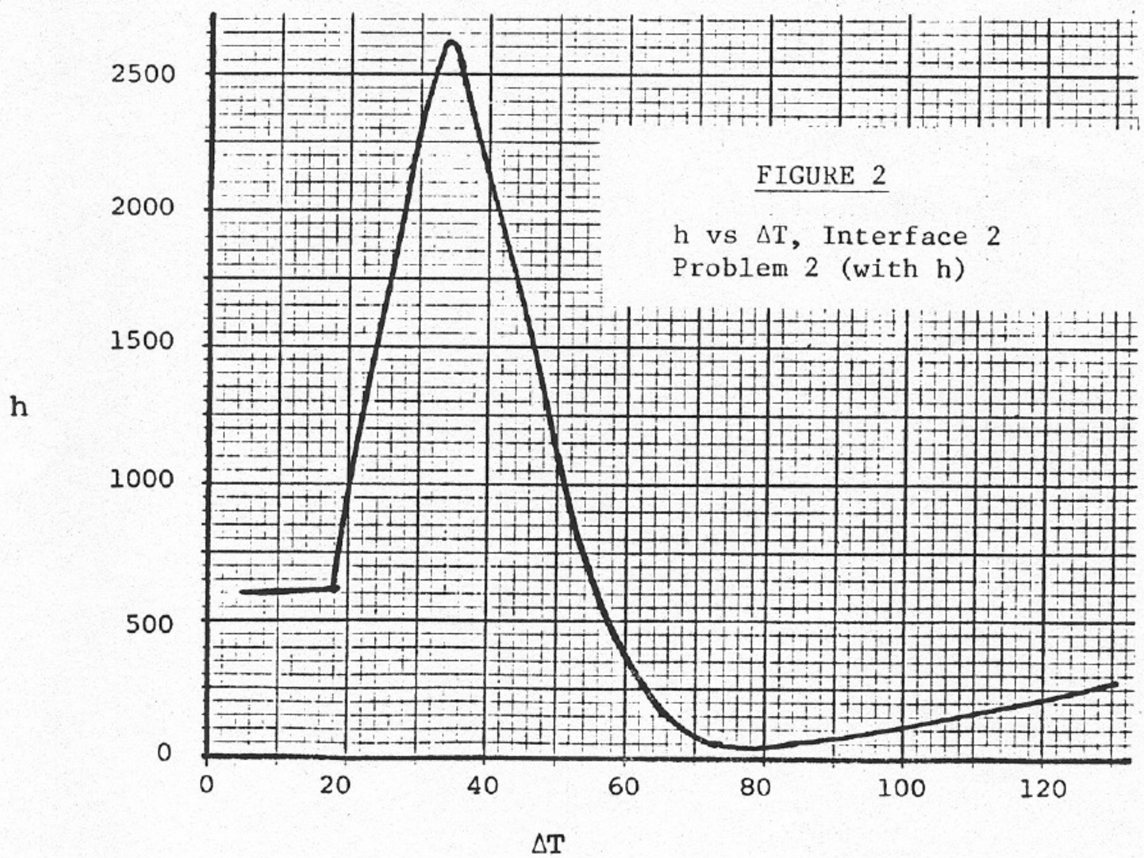

FIGURE 2

h vs ΔT, Interface 2
Problem 2 (with h)

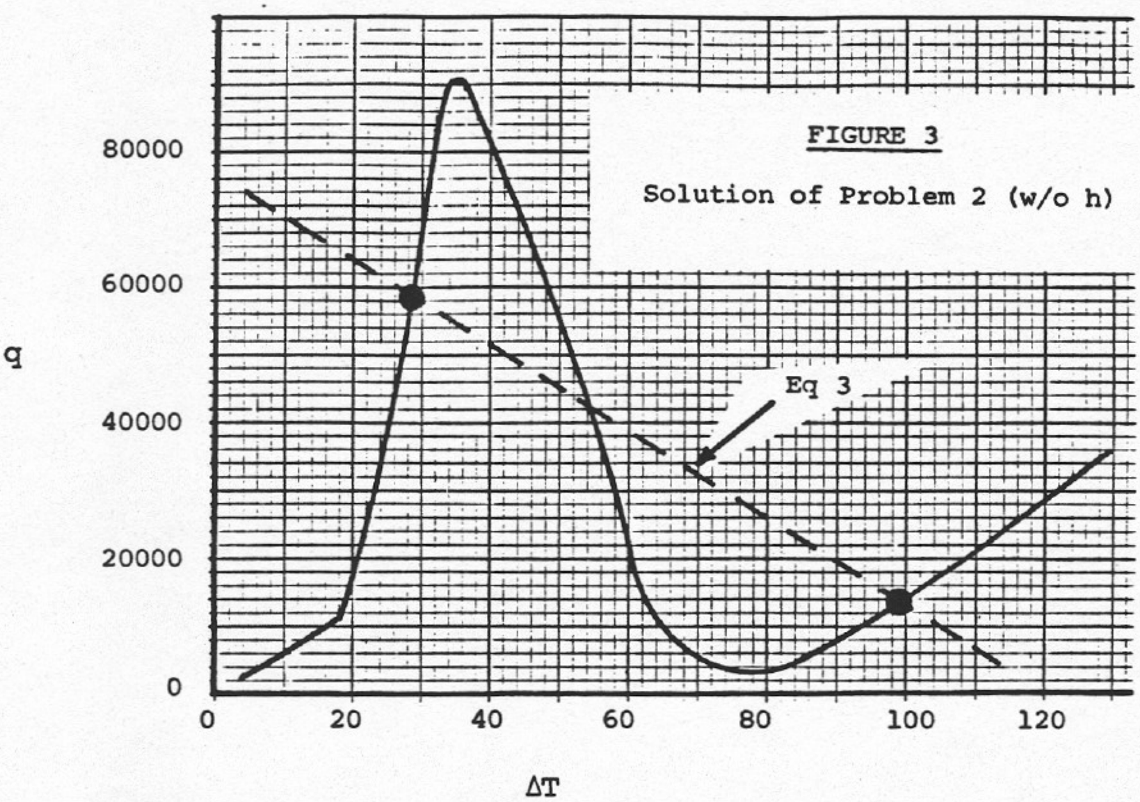
FIGURE 3
Solution of Problem 2 (w/o h)
Eq 3
q
80000
60000
40000
20000
0
0
20
40
60
80
100
120
ΔT

APPENDIX A

Reproduction of page 1 of Newton's "A Scale of the Degrees of Heat"--from an English translation which was published by the Royal Society in 1749--see Ref 2 in text

The Philosophical Transactions

ABRIDG'D.

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.
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