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A Critical Appraisal of Conventional Methodology used to Determine Heat Transfer Correlations, and Alternate Methodology

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Three examples in the text apply the alternate methodology to data in the literature, and compare the resultant correlations to widely accepted correlations based on conventional methodology and the same data. The correlations that result from the alternate methodology agree with the underlying data much more accurately than correlations that result from conventional methodology. The difference in accuracy reflects the fact that deduction is much more difficult than induction, and therefore much more likely to include errors, and less likely to accurately describe the underlying data.

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A Critical Appraisal of Conventional Methodology used to Determine Heat Transfer Correlations, and Alternate Methodology

Eugene F. Adiutori

Abstract- This article describes alternate methodology for determining heat transfer correlations from experimental programs. In conventional methodology, the *form* of heat transfer correlations is determined *before* the experiment by *deduction*, and the experiment is performed in order to quantify constants in the deduced correlation form. In the proposed alternate methodology, the *form* of heat transfer correlations is determined *after* the experiment by *induction*.

Three examples in the text apply the alternate methodology to data in the literature, and compare the resultant correlations to widely accepted correlations based on conventional methodology and the *same data*. The correlations that result from the alternate methodology agree with the underlying data much more accurately than correlations that result from conventional methodology. The difference in accuracy reflects the fact that deduction is much more difficult than induction, and therefore much more likely to include errors, and less likely to accurately describe the underlying data.

One of the examples concerns film heating/cooling, a process widely used to deice airplanes in flight, and to cool internal components in gas turbines. The other two examples concern the relationship between heat flux and boundary layer temperature difference in the nucleate boiling region, and in the transition boiling region.

I. REVIEWS OF FILM HEATING/COOLING STUDIES

Kays (1966) presents a brief review of film cooling/heating effectiveness studies. Kays states:

... there is a considerable body of experimental data, the results of which can be presented in a simple manner. . . . It is found that η is primarily a function of a blowing rate parameter m . . . the width (or height) of the injection slot s , and the distance x . . . Wieghardt (1946) presents the correlation . . .

$$\eta = 21.8(x/ms) \quad 0.22 < m < 0.74 \quad x/s > 100 \quad (1)$$

Acharya and Kanani (2017) present a comprehensive review of film cooling/heating studies made since 1946. All correlations in the review are based on the group parameter x/ms , including correlations by Bunker (2006) and Colban et al (2011). Most correlations are in the form of Eq. (2). Several are in the form of Eq. (3).

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$$\eta = f\{x/ms\} \quad (2)$$

$$\eta = f\{m, x/ms\} \quad (3)$$

Wieghardt's (1946) pioneering study of film heating, and the conventional methodology that typically underlies the form of film heating/cooling correlations.

In a pioneering study, Wieghardt (1946) determined a correlation for film heating. Data were obtained from a system in which film heating air entered the mainstream from a tangential slot. Data were obtained at m values from 0.22 to 1.90, a slot height of 10 mm, mainstream air velocities of 16 and 32 m/sec, heating air velocities of 8 to 40 m/sec, and temperature differences of 30 to 60 C between mainstream air and film heating air.

Wieghardt *a priori*:

- Deduced that the important parameters in film heating are η , x , m , and s .
- Deduced that equations in the form of Eq. (4) correlate film heating data.

$$\eta = f\{x\}f\{m\}f\{s\} \quad (4)$$

- Deduced that each function in Eq. (4) is the parameter raised to an exponent, as in Eq. (5).

$$\eta = ax^b m^c s^d \quad (5)$$

- Because it is assumed that rational equations are dimensionally homogeneous, deduced that d and b in Eq. (5) are equal, resulting in Eq. (6).

$$\eta = ax^b m^c s^{-b} \quad (6)$$

- Deduced that, because the s exponent equals the negative of the x exponent, and because the data include a wide range of x values, the s exponent can be determined from the $\eta\{x\}$ data, and therefore the experiment requires only one value of s .

Note that, before any data were obtained, everything about the film heating correlation had been deduced except the values of the constants in Eq. (6).

The constants in Eq. (6) were quantified after the experiment by induction, and Eq. (7) resulted.

$$\eta = 21.8(x/ms)^{-.8} \quad x \geq 100s \quad m \leq 1.0 \quad (7)$$

The restrictions on the application of Eq. (7) are required because:

- Eq. (7) does *not* agree with the data if x is less than 100s.
- The data indicate that, at $x = 100s$, $d\eta/dm$ becomes *negative* at $m = 1.0$.

Note that in Eq. (7), η is inversely related to x . Therefore Eq. (7) indicates that η equals *infinity* at $x = 0$, whereas η cannot exceed 1.000.

The problem with the a priori deduction that η depends on x , m , and s

It is axiomatic that a parametric correlation should be expressed in terms of *independent* parameters so that the correlation is affected by *every* parameter in the correlation.

The problem with the *a priori* deduction that η depends on x , m , and s is that m is *not* independent of s . m is inversely proportional to s , and consequently the *product* ms does *not* depend on m or s . Therefore the parameter group x/ms does *not* depend on m or s , and consequently Eq. (7) seems to state that η depends on m and s , when in fact Eq. (7) states that η does *not* depend on m or s . Note that:

- Identity (8) indicates that m is inversely proportional to s .

$$m \equiv G_{slot}/G_{ms} \equiv (W_{slot}/sW_{slot})/G_{ms} \equiv W'_{slot}/(G_{ms}s) \quad (8)$$

- Identity (9) indicates that, in terms of *independent* parameters, ms is W'_{slot}/G_{ms} . In other words, the *product* ms does *not* depend on m or s . It depends on W'_{slot} and G_{ms} .

$$ms \equiv (W'_{slot}/(G_{ms}s))s \equiv W'_{slot}/G_{ms} \quad (9)$$

- Identity (10) indicates that, in terms of *independent* parameters, x/ms is xG_{ms}/W'_{slot} .

$$x/ms \equiv xG_{ms}/W_{slot} \quad (10)$$

- Combining Identity (10) and Eq. (7) results in Eq. (11). Eqs. (7) and (11) are *identical*. Both equations state that η depends on x , G_{ms} , and W_{slot} . Both equations state that η does *not* depend on m or s .

$$\eta = 21.8 (xG_{ms}/W'_{slot})^{-.8} \quad x \geq 100s \quad m \leq 1.0 \quad (11)$$

- Eq. (11) should replace Eq. (7) because Eq. (7) seems to state that η depends on m and s , when in fact it states that η does *not* depend on m or s . Both equations state that η depends on x , G_{ms} , and W'_{slot} .
- Because Eqs. (7) and (11) state that η does *not* depend on m , any effect that m has on η necessarily contributes to the disagreement between the data and Eqs. (7) and (11). (Recall that s was *not* varied in the experiment, and therefore variation in s could not have contributed to the disagreement between the data and Eqs. (7) and (11).)

In summary, the problem with the *a priori* deduction that η depends on x , m , and s is that this

deduction is largely responsible for Eq. (7), an equation that appears to state that η depends on x , m , and s , when in fact it states that η depends on x , G_{ms} , and W'_{slot}

The problem with the a priori deduction that equations in the form of Eq. (4) correlate film heating data

The problem with the *a priori* deduction that an equation in the form of Eq. (4) best correlates film heating data is that there is no sound reason to conclude that film heating data are best correlated by an equation that indicates η is a function of the product of each parameter raised to an exponent.

The problem with the a priori deduction that equations in the form of Eq. (6) correlate film heating data

The problem with the *a priori* deduction that equations in the form of Eq. (6) correlate film heating data is that η is inversely related to x , and therefore Eq. (6) states that η equals *infinity* at $x = 0$, whereas η cannot be greater than 1.00.

Note that Eqs. (7) and (11) are in the form of Eq. (6), and they do *not* correlate the data if x is less than 100s. For example, if the slot height is 10 mm as in Wiegardt (1946), Eqs. (7) and (11) do *not* correlate film heating data in the first 1000 mm directly downstream of the slot exit.

The problem with the a priori deduction that the relationship between η and s can be experimentally determined without varying s

The only way to experimentally determine the relationship between η and s is to test more than one value of s . Because the Wiegardt test program included only one value of s , the test data do *not* establish the relationship between η and s . Therefore Eq. (7) should either:

- *Not* include parameter s , and be accompanied by the statement " $s = 10$ mm." to inform the user that the correlation is based on data obtained at $s = 10$ mm.
- Or include parameter s and be accompanied by the statement " $s = 10$ mm." to inform the user that the $\eta\{s\}$ functionality in the correlation is *not* supported by data.

The film heating correlation by Hartnett, Birkebak, and Eckert (1961)

Hartnett, Birkebak, and Eckert (1961) performed a film heating experiment using a tangential slot similar to that used by Wiegardt, a slot height of 3.12 mm, an m value of 0.28, a mainstream velocity of 51 m/sec, and temperatures differences of 5 to 80 C between the film air and the mainstream air. The authors state:

The usual choice of parameters was made to represent the data. These same parameters are suggested in a semiempirical analysis presented in the Appendix . . .

It was *a priori* deduced or assumed that an equation in the form of Eq. (7) would best correlate their film heating data. The authors plotted their data on the log log chart in their Fig. (24), drew a line through their data, and concluded that the line indicates that the coefficient in Eq. (7) should be 16.9 rather than the 21.8, resulting in Eq. (12).

$$\eta = 16.9(x/ms)^{-0.8} \quad (12)$$

$x/s > 17 \quad m = .28 \quad s = 3.12 \text{ mm.}$

Note that Eq. (7) closely correlates its underlying data only if x/s is greater than 100, whereas Eq. (12) closely correlates its underlying data if x/s is greater than 17.

With regard to the discrepancy between coefficients 21.8 and 16.9 in Eqs. (7) and (12), Hartnett, Birkebak, and Eckert (1961) state:

... we would expect that the value of Wieghardt's constant (21.8) would be less than 16.9 as found in this investigation ... This inconsistency may possibly be the result of an inaccurate measurement by Wieghardt of the entering injectant air temperature T_{slot} ...

However, as noted above, Eqs. (7) and (12) state that m and s have *no effect* on η . Therefore, if m or s *does* affect η , the difference in m or s values between the two studies could explain the inconsistency noted above.

In the Wieghardt study, s was 10 mm, and the correlation was based on m values from 0.22 to 1.0. In the Hartnett, Birkebak, and Eckert study, s was 3.12 mm and m was 0.28. Note that there is a factor of 3 difference between s values, and a factor of 2 difference in average m values. Hartnett, Birkebak, and Eckert state:

If Wieghardt's correlation is modified to represent only his lower blowing rates, $m \leq 0.40$... , the constant is changed from 21.8 ... to 19.5.

This statement indicates that:

- The value of m or s *does* affect η .
- m should be a parameter in film heating correlations. (Note that several correlations cited in Acharya and Kanani (2017) are in the form $\eta = f\{m, x/ms\}$, indicating that m *does* affect η .)
- The discrepancy between coefficients 21.8 and 16.9 in Eqs. (7) and (12) resulted, at least in part, because m and s in the two studies were vastly different, whereas Eqs. (7) and (12) state that η does *not* depend on m or s .

Using alternate methodology to determine the best correlation for the data presented in Hartnett, Birkebak, and Eckert (1961)

The film heating experiment by Hartnett, Birkebak, and Eckert (1961) included only one value of

G_{ms} and one value of W'_{slot} . Consequently the data provide information about $\eta\{x\}$, but no information about $\eta\{x/ms\}$. Therefore we can determine the best $\eta\{x/ms\}$ correlation for the subject data only if the analysis is based on the *a priori* conclusion that the best correlation form for film heating data is $\eta\{x/ms\}$.

In order to determine the best $\eta\{x/ms\}$ correlation for the subject data, it is necessary to determine the $\eta\{x/ms\}$ correlation that best describes the line drawn by the authors through their x/ms data plotted on the log log chart in their Fig. (24). Since η cannot exceed 1.00, the best film heating correlation *must* be in a form in which the calculated value of η cannot exceed 1.00. Equation (13) is a correlation form in which η cannot exceed 1.00. Eq. (13) is plotted on the log log data chart in Fig. (24), and the optimum value of c is determined by trial and error.

$$\eta = 1/(1.00 + c(x/ms)) \quad (13)$$

Eq. (14) is the resultant correlation. Adiutori (1974) states that Eq. (14) correlates *all* of the subject data so well that it is not possible to *distinguish between Eq. (14) and the curve drawn by the authors through their experimental points* plotted on their Fig. 24.

$$\eta = 1/(1.00 + .0142(x/ms)) \quad (14)$$

$x \geq 0 \quad m = 0.28 \quad s = 3.12 \text{ mm.}$

Eq. (14) is much more accurate than Eq. (12) because Eq. (14) closely agrees with *all* of the data presented in Hartnett, Birkebak, and Eckert (1961), whereas Eq. (12) closely agrees with the data only at x/s values greater than 17.

It is important to note that Eq. (14) describes the relationship between x , m , and s (ie. x , G_{ms} , and W'_{slot}) at only one value of m and one value of s . Consequently Eq. (14) in fact describes only the relationship between η and x .

II. BOILING HEAT TRANSFER STUDY BY NUKIYAMA (1934)

Nukiyama (1934) was a pioneering study of boiling heat transfer in which nucleate boiling and film boiling heat transfer data were obtained from electrically heated wires and flat surfaces immersed in water at atmospheric pressure. The data were plotted on linear coordinates, and the resultant charts indicate the following:

- In fully developed nucleate boiling, the relationship between heat flux q and boundary layer temperature difference ΔT is usually quite *linear*, and is described by equations in the form of Eq. (15). Note that q_{onb} is the heat flux at the onset of fully developed nucleate boiling, and ΔT_{onb} is the temperature difference at the onset of fully developed nucleate boiling. ΔT_{DNB} is the

temperature difference at the departure from nucleate boiling.

$$q_{nb} = q_{ofnb} + a(\Delta T - \Delta T_{ofnb}) \quad \Delta T_{ofnb} \leq \Delta T \leq \Delta T_{DNB} \quad (15)$$

- In fully developed nucleate boiling, the relationship between q and ΔT is sometimes slightly nonlinear, and is described by equations in the form of Eq. (16) in which $n \cong 0.8$.

$$q_{nb} = q_{ofnb} + a(\Delta T - \Delta T_{ofnb})^n \quad \Delta T_{ofnb} \leq \Delta T \leq \Delta T_{DNB} \quad (16)$$

A priori deduction or assumption that results in the widely accepted conclusion that nucleate boiling heat transfer data describe highly nonlinear power laws

In spite of Nukiyama's data that documented highly *linear* behavior in the nucleate boiling region, for almost 100 years it has been widely agreed in American engineering literature that nucleate boiling heat transfer data describe highly *nonlinear* power laws¹ in the form of Eq. (17), such as the widely accepted Rohsenow correlation in which $n = 3$.

$$q = f\{\Delta T^n\} \quad (17)$$

The graphical methodology that results in highly nonlinear power laws is described in Cryder and Finalbargo (1937). This methodology is based on the *a priori* deduction or assumption that nucleate boiling data describe nonlinear power laws.

To determine (the relationship between heat transfer coefficient and temperature difference), the coefficient (h) . . . is plotted against ΔT . . . at constant boiling temperature. A log-log plot . . . results in a series of straight lines with a slope of 2.5. . . The data would therefore indicate that (h { ΔT } is a power law of exponent 2.5—ie $q\{\Delta T\}$ is a power law of exponent 3.5.)

The digital methodology that results in highly nonlinear power laws is described in Cooper (1984). This methodology is also based on the *a priori* deduction or assumption that nucleate boiling data describe nonlinear power laws.

Correlations in the form of (power laws) are produced directly from raw data by a . . . least squares program. . . Here the fit is among $\log h$, $\log q$.

The problem with the a priori deduction or assumption that nucleate boiling data describe highly nonlinear power laws

Adiutori (1994) states that the problem with the *a priori* deduction or assumption that nucleate boiling data describe highly nonlinear power laws is that it results in induction methodology that is *not* rigorous. Adiutori (1994) states:

¹ A few nucleate boiling heat transfer studies, such as Mesler and Banchemo (1958), correctly concluded that nucleate boiling data describe highly *linear* behavior. However, they are seldom cited.

Rigorous induction methodology is achieved by plotting data in linear coordinates and fitting a curve through regions which contain closely spaced data.

Induction should be based on data plotted on *linear* charts because functionality is readily apparent on linear charts, whereas functionality is distorted and *not* readily apparent on log log charts.

A nucleate boiling heat transfer correlation based on alternate methodology

In alternate methodology, nucleate boiling correlations are determined by "*plotting data in linear coordinates and fitting a curve through regions which contain closely spaced data*". This was in fact the methodology used by Nukiyama (1934).

Alternate methodology results in the conclusion that literature data indicate that nucleate boiling heat transfer data are *not* generally correlated by *nonlinear* power laws in the form of Eq. (17). As Nukiyama concluded, nucleate boiling heat transfer data are generally correlated by *linear* equations in the form of Eq. (15).

Adiutori (1994) states:

- *Examples of data originally judged to support the linear view are those of Nukiyama (1934) and Mesler and Banchemo (1958).*
- *Examples of data originally judged to support the power law view, and later shown to be highly linear, are those of Perry (1948), Cichelli and Bonilla (1945), Corty (1951), Stock (1960), Aladiev (1960), and Berenson (1960 and 1962).*
- *Data cited by Rohsenow (1952) to validate his widely accepted power law correlation in fact exhibit linear behavior.*

The a priori deduction or assumption that transition boiling heat transfer data describe nonlinear power laws

Transition boiling data in heat transfer literature are generally plotted on logarithmic charts presumably because of the *a priori* deduction or assumption that transition boiling heat transfer data describe nonlinear power laws with negative exponent.

For example, Berenson (1960 and 1962) obtained data on 20 boiling curves using a vented pool boiler with a round, flat boiler plate which was steam heated on the lower surface. The boiling fluid was n-pentane, and the boiling surfaces tested were nickel, copper, and inconel. The data were plotted on log log charts, and straight lines drawn through transition boiling regions. Berenson (1962) concluded the following about the transition boiling region:

It was found, with the exception of some of the data presented in Fig. 5, that the transition boiling data lie along a straight line connecting the burnout point and the film-boiling minimum point on log log graph paper. This is also true of the transition boiling data

obtained by Braunlich (1941) and Kaulakis and Sherman (1938).

In summary, three experiments for doctoral theses performed at MIT over a period of more than 20 years independently concluded that “transition boiling data lie along a straight line connecting the burnout point and the film-boiling minimum point on log log graph paper”.

The problem with the a priori deduction or assumption that transition boiling heat transfer data describe nonlinear power laws

Due to the vagaries of log log charts, it was not noticed that seventeen of Berenson’s twenty boiling curves contain little or no data in the transition boiling region. Consequently straight lines were drawn through the transition region of seventeen boiling curves that have little or no data in the transition region.

Three of the boiling curves (Runs 7, 8, and 9) contain data throughout the transition boiling region. (Runs 7, 8, and 9 contain the data referred to in the phrase “with the exception of some of the data presented in Fig. 5”.) The transition boiling region data from Runs 7, 8, and 9 lie on highly curved lines on log log charts.

$$q_{tb} = q_{max} - (q_{max} - q_{min})(\Delta T - \Delta T_{max q}) / (\Delta T_{min q} - \Delta T_{max q}) \quad \Delta T_{max q} \leq \Delta T \leq \Delta T_{min q} \quad (18)$$

Hesse (1973) obtained transition boiling data using an apparatus in which boiling takes place on the outer surface of a thin wall tube made of nickel; the boiling fluids tested were R112, R113, and R114; tests were performed at pressures from 0.5 to 20 bars; the heat source was water pumped at high velocity through the tube. Boiling curve data were obtained, and the data plotted on log q vs log ΔT charts. In the transition boiling region, the data describe curved lines on log log charts, and straight lines on linear charts. (The linear charts are in Adiutori (1991).)

Ellion (1954) was the first to design and build an electrically heated, forced convection boiler that could operate stably in the transition boiling region. The boiler was a double tube heat exchanger in which the boiling interface was the outer surface of the inner tube. When Ellion’s boiling data are plotted on linear coordinates, the data from three of the runs are highly linear in the transition region, and the data from one of the runs is curved in the transition region. (The linear charts are in Adiutori (1991).)

McDonough et al (1961) reported the first transition boiling experiment at high pressure. The boiler in the experiment was a double tube, counter flow heat exchanger in which boiling water flowed upward inside the inner tube. Linear equations were induced from transition region data.

Ragheb et al (1978) investigated transition region boiling. The results presented in Ragheb et al

The problem with the *a priori* assumption or deduction that transition boiling heat transfer data describe nonlinear power laws is that transition boiling heat transfer data do *not* describe nonlinear power laws, as evidenced by the fact that transition boiling heat transfer data do *not* describe straight lines on log log charts.

Using alternate methodology to determine correlations for transition boiling heat transfer

If alternate methodology is used, correlations for transition boiling heat transfer are determined by plotting data on *linear* charts, and determining functionality by inspecting the chart.

If Berenson’s 20 boiling curves are plotted on linear charts, it is apparent that 17 curves have little or no data in the transition region, and curves for Runs 7, 8, and 9 have data throughout the transition region. On linear charts, data from Runs 7, 8, and 9 describe straight lines between the maximum and the minimum in the boiling curve, indicating that the relationship between heat flux and temperature difference in the transition boiling region is described by *linear* equations in the form of Eq. (18). (A linear chart of Runs 7, 8, and 9 is in Adiutori (1974).)

(1978) are reported in digital form in ANL reports. For example, boiling curve data for a mass flow rate of 203 kg/m²s and sub cooling values of 0, 13.9, and 27.8 C are reported in digital form in Cheng et al (1978). When these data are plotted on linear coordinates, the transition boiling data describe straight lines. (The linear chart is in Adiutori (1991).)

In summary, the problem with the *a priori* assumption or deduction that transition boiling heat transfer data describe nonlinear power laws is that transition boiling heat transfer data in the literature generally describe *linear* equations in the form of Eq. (18).²

Conventional methodology used to determine the generic correlation for heat transfer to a turbulent, one phase Newtonian fluid

In conventional methodology, the generic correlation for heat transfer to a turbulent, one phase Newtonian fluid is based on the following *a priori* deduction:

- Deduce that h depends on D, G, k, C_p, and μ.
- Deduce that the h correlation is in the form of Eq.

$$h = f\{D\}f\{G\}f\{k\}f\{C_p\}f\{\mu\} \quad (19)$$

² If transition boiling data describe straight lines on log log charts rather than linear charts, dq/dΔT is much more negative in the upper end of the transition region. This has practical importance in analyses to determine fuel temperature transients following a loss of coolant flow in water cooled nuclear reactors.

- Deduce that each function in Eq. (19) is the parameter raised to an exponent, as in Eq. (20).

$$h = aD^b G^c k^d C_p^e \mu^f \quad (20)$$

- Deduce that the values of the constants in Eq. (20) are the same for all Newtonian fluids.
- Deduce that Eq. (20) is dimensionally homogeneous.
- Use dimensional analysis to deduce that Eq. (20) can be replaced by Eq. (21).

$$Nu = aRe^b Pr^c \quad (21a)$$

$$h = ak^{1-c} D^{b-1} G^b \mu^{c-b} C_p^c \quad (21b)$$

The problem with the deduction that h equals the product of each correlating parameter raised to an exponent

The problem with the deduction that h equals the product of each correlating parameter raised to an exponent is that there is no basis for it. It is a deduction without foundation.

Recall that the film heating correlations by Wiegardt (1946) and by Hartnett, Birkebak, and Eckert (1961) are based on the deduction that η equals the product of each correlating parameter raised to an exponent, and both correlations violently *disagree* with much of the data. Also recall that the film heating correlation that resulted from applying the alternate methodology to the data by Hartnett, Birkebak, and Eckert does *not* state that η equals the product of each parameter raised to an exponent, and that correlation agrees with *all* of the data.

If alternate methodology is used, it is not *a priori* deduced that correlations are the product of each important parameter raised to an exponent. Correlation functionality is determined *a posteriori* by induction, and *all* functions are acceptable.

a) The problem with Equation (21)

The problem with Eq. (21) is that it has *nothing to do with data*. It is *entirely* the result of a *priori* deduction. Data are required merely to quantify a , b , and c in Eq. (21).

Note that the accuracy and validity of Eq. (21) are suspect because:

- There is no sound basis for the assumption that correlations are generally the product of important parameters raised to exponents.
- There is no sound basis for the assumption that a correlation that applies to *all* Newtonian fluids can be determined by a test program in which only one Newtonian fluid is tested.
- The relationship between μ and h is determined *without* measuring μ .
- The relationship between k and h is determined *without* measuring k .
- The relationship between C_p and h is determined *without* measuring C_p .

- It indicates that the exponents of D and G are both dependent on b , and therefore the D exponent can be determined without varying D .

Eq. (22a) is a generally accepted correlation determined primarily by the *a priori* deduction described above. Note that Eqs. (22a) and (22b) are identical, and that Eq. (22b) is in a much more useful form in that it *reveals* parameter functionality because parameters are *explicit*, whereas Eq. (22a) *conceals* parameter functionality because parameters are *implicit* in group parameters. Also note that Eq. (22a) *cannot* be used to determine h unless it is first transformed to Eq. (22b).

$$Nu = .023Re^8 Pr^4 \quad (22a)$$

$$h = .023 D^{-2} G^8 k^6 \mu^{-4} C_p^4 \quad (22b)$$

b) "Scientific" correlations

The word "scientific" is generally considered synonymous with "rigorously correct". Parametric correlations are generally considered scientific if they are primarily the result of a *priori* deduction, and considered *unscientific* if they are primarily the result of a *posteriori* induction.

But the truth is just the opposite. As evidenced by the above film heating correlations and the boiling correlations, correlations that are primarily the result of rigorous *a posteriori* induction are likely to be much more correct—much more scientific—than correlations that are primarily the result of a *priori* deduction.

Engineering laws such as Hooke's law and Ohm's law are "scientific", but they are *not* primarily the result of a *priori* methodology. They are primarily the result of a *posteriori* induction.

Newton's view of the scientific method

In a letter to Father Pardies, Newton (1672) described his view of the scientific method in the following:

The best and safest method of philosophizing seems to be, first to enquire diligently into the properties of things, and to establish these properties by experiment, and then to proceed more slowly to hypothesis for the explanation of them. For hypotheses should be employed only in explaining the properties of things, but not assumed in determining them . . .

In other words, in Newton's view of the scientific method, parametric correlations should be determined by a *posteriori* induction rather than a *priori* deduction.

A priori deduction if alternate methodology is used to determine a fluid specific correlation for heat transfer to a turbulent, one phase Newtonian fluid

If alternate methodology is used to determine a fluid specific correlation for heat transfer to a turbulent, one phase Newtonian fluid, it is a *priori* deduced that a

correlation in the form of Eq. (23) will correlate the data. The functions in Eq. (23) are determined *a posteriori*, and any function that closely describes the data is acceptable.

$$h = a f\{G\} f\{D\} f\{T_{fluid}\} \quad (23)$$

If the data do not verify that Eq. (23) correlates the data, a different correlation form is deduced.

Fluid specific heat transfer correlations that result from alternate correlation methodology

If alternate methodology is used:

- The resultant correlation includes only parameters measured in the experiment.
- Parameters in fluid specific correlations are *explicit* rather than implicit in group parameters such as Re.
- Fluid specific correlations are desirable because:
 - They more accurately describe the heat transfer behavior of the specified fluid than fluid generic correlations.
 - They are more user friendly in that they do not require reference to property tables.
 - They more readily reveal functionality.
- Fluid specific correlations such as Eq. (23) *cannot* be dimensionally homogeneous because G is the only parameter that includes the dimension of mass. Correlations that are not dimensionally homogeneous must be in the form of “dimensional equations”, a form widely used in mid-twentieth century.

In dimensional equations, parameter symbols represent numerical value but *not* dimension, and the dimension units that underlie parameter symbols are specified in an accompanying nomenclature. The following is an example of a “dimensional equation”:

For the turbulent flow of gases in straight tubes, the following dimensional equation for forced convection is recommended for general use:

$$h = 16.6 c_p (G)^{0.8} / (D_i)^{0.2}$$

where c_p is the specific heat of the gas at constant pressure, B.T.u./((lb.)°F), G' is the mass velocity, expressed as lb. of gas/sec./sq. ft. . . . and D_i is in inches. Perry (1950)

The design of an experimental study to determine a fluid specific correlation for heat transfer to a turbulent, one phase Newtonian fluid

The design of an experimental study to determine a fluid specific correlation for heat transfer to a turbulent, one phase Newtonian fluid is shown in Table 1. The numbers in the table represent the relative values

of the parameters. Table 1 indicates that each parameter is to be tested at 5 values while the other parameters are at their lowest value, and at the same 5 values while the other parameters are at their highest values.

Table 1: Experiment Design

G	T_{fluid}
1	1 to 5
5	1 to 5
1 to 5	1
1 to 5	5

Table 1 indicates that 20 data points are required for each diameter tested, 10 to determine $f\{G\}$ and $f\{T_{fluid}\}$, and 10 to verify that the effect of each parameter is independent of the value of the other parameters. Since Eq. (22b) indicates that q is a weak function of D, the experiment design would reasonably call for only three values of D, and the entire experiment would require 60 data points.

How a fluid generic correlation can be determined from a fluid specific correlation

A fluid generic correlation can be determined from a fluid specific correlation as follows:

- Assume that Eq. (24) applies. Note that $f\{T_{fluid\ x}\}$ is from a fluid specific correlation for fluid x, and k, C_p , and μ are functions of $T_{fluid\ x}$.

$$f\{T_{fluid\ x}\} = k^a C_p^b \mu^c \quad (24)$$

- Use $f\{T_{fluid\ x}\}$ data to determine optimum values of a, b, and c in Eq. (24), or use the corresponding exponents in Eq. (22b).

In the fluid specific correlation, replace $f\{T_{fluid\ x}\}$ with the right side of Eq. (24), resulting in a fluid generic correlation. The generic correlation should be accompanied by a statement such as “This fluid generic correlation is based on a fluid specific correlation for fluid x, and the assumptions that:

- $f\{D\}$ and $f\{G\}$ are the same for all Newtonian fluids.
- The values of a, b, and c in Eq. (24) are the same for all Newtonian fluids. (Or “The values of a, b, and c are from Eq. (22b))”

III. CONCLUSIONS

Methodology that is primarily a *a posteriori* induction should be used to determine parametric correlations because, as the examples in the text demonstrate, it results in correlations that more closely agree with data than methodology that is primarily a *a priori* deduction.

Symbols

a to f constants
 C_p heat capacity

D	diameter
G	mass flow rate
h	$q/\Delta T$ thermal conductivity
m	$G_{\text{slot/Gms}}$
n	constant
Nu	Nusselt number
Pr	Prandtl number
q	heat flux
Re	Reynolds number
s	slot height
T	temperature
w	slot width
W	flow rate
W'	flow rate per unit slot width
x	distance downstream of slot exit
μ	viscosity
η	film effectiveness

Subscripts

DNB	departure from nucleate boiling
Max	maximum in the boiling curve
Min	minimum in the boiling curve
Ms	main stream
Nb	nucleate boiling
Ofdnb	onset of fully developed nucleate boiling
Tb	transition boiling

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