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A New and Simple Concept to Replace "Film Effectiveness"

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ABSTRACT

Film effectiveness (η) is used to describe the adiabatic wall temperature (TAW) which results when a colder or hotter fluid is injected into the boundary layer. Eq (1) is the defining equation for η:

$$(TMS - TAW) = \eta(TMS - TF) \tag{1}$$

where TF and TMS refer to the temperatures of the film and mainstream fluids.

Literature data indicate that η is a constant coefficient in Equation 1 only in applications where TF/TMS is restricted to a narrow band. If TF/TMS varies over a wide band, such as in gas turbines and rockets, then η is a *variable* in Eq 1.

This article demonstrates that, in applications where TF/TMS varies over a wide band, the film effectiveness concept is neither simple nor direct, and it complicates and confuses the solution of practical problems.

This article also presents a new and simple concept to replace film effectiveness. The new concept retains the TF/TMS parameter used in film effectiveness methodology, but it replaces η with TAW/TMS.

The particular advantage of the new concept is that it describes TAW in a simple and direct way even if TF/TMS varies over a wide band. The end result is that, in applications such as gas turbines and rockets, the new concept is much simpler and therefore much better than the film effectiveness concept it replaces.

THE FILM EFFECTIVENESS CONCEPT--ASSET OR LIABILITY?

The film effectiveness concept has been used for approximately fifty years to describe the adiabatic wall temperature which results when a fluid is injected into the boundary layer. Eq (1) is the defining equation for film effectiveness (η):

$$(TMS - TAW) = \eta(TMS - TF) \tag{1}$$

If η is independent of TF and TMS, then η is the constant of proportionality in Eq (1), and Eq (1) is written

$$TAW = TMS - \eta(TMS - TF) \tag{2}$$

to indicate that η is a *constant coefficient* in a *linear* equation.

But if the value of η is dependent on TF and TMS, Eq (2) should be written

$$TAW = TMS - \eta\{TF,TMS\}(TMS - TF) \tag{3}$$

to indicate that η is a *variable* in a *nonlinear* equation.

In order to determine whether η is an asset or a liability, it is necessary to determine whether η is a constant coefficient in a linear equation, or a variable in a nonlinear equation.

THE EARLY VIEW OF FILM EFFECTIVENESS BEHAVIOR

The early view of film effectiveness behavior held that η is independent of TF and TMS, and therefore that η is a constant coefficient in a linear equation. This assumption (or deduction) greatly simplified the task of experimentally determining film effectiveness correlations because it meant that the underlying experiments could be performed at whatever temperatures were most convenient, and that test matrixes need not include variation in TF or TMS.

Wieghardt (1946) is generally considered the pioneer of film heating and cooling. He correlated film heating data in the form

$$\eta = f\{x/ms\} \tag{4}$$

This form indicates that η is independent of TF and TMS, and therefore that η is a constant coefficient in a linear equation. Thus Wieghardt's correlation describes the TAW which would result from any and all values of TF and TMS.

In the 1950's and 60's, many film cooling and film heating experiments were performed. Since most researchers assumed or deduced that η is independ-

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ent of TF and TMS, experiments were usually performed at near ambient conditions, and test matrixes usually included little or no variation in TF or TMS.

Seban (1960) describes the view of film effectiveness widely held in 1960:

> *When (a film heated) plate is insulated, the effect of the film injection can be characterized COMPLETELY in terms of the ratio of the excess of plate over free-stream temperature to the excess of the injected air over the free-stream air temperature. This ratio is called the effectiveness.*

In line with this view, Seban (1960) presents a film effectiveness correlation in the form of Eq (5). He describes the underlying experiment as follows:

> *temperatures in the free stream were between 50 F and 70 F and . . . practically all effectiveness determinations (were) made with (a film temperature 70 F above the free stream) temperature".*

$$\eta = f(x/s)\, f(m) \qquad (5)$$

Notice in Eq (5) that η is independent of TF and TMS, and therefore η is a constant coefficient in a linear equation. Eq (5) establishes TAW for all TF and TMS, even though the underlying experiment was performed at essentially *one* TF and *one* TMS.

Similarly, Hartnett, Birkebak, and Eckert (1961) performed a film heating experiment in which TMS was at ambient temperature, and TF was 10 to 150 F *above* ambient. The authors demonstrated that this variation in film temperature had little effect on η, and they correlated their data in the same form used by Wieghardt:

$$\eta = f(x/ms) \qquad (6)$$

The authors state that their correlation gives "*a good approximate value of TAW*" for film *cooling* applications such as gas turbines and rockets, even though the underlying experiment was a film *heating* experiment performed at near ambient conditions.

Kays (1966) summarizes the literature data, and indicates that η is generally considered to be quite independent of TF and TMS. He 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 height of the injection slot s, and the distance x.*

The view that η is essentially independent of TF and TMS has largely disappeared from the literature. However, it persists on a considerable scale in industry, and is occasionally found even in 1990 journals.

AN EARLY DISSENTING VIEW OF FILM EFFECTIVENESS BEHAVIOR--BY PAPPELL AND TROUT (1959)

Papell and Trout (1959) performed a film experiment in which TF and TMS were varied over a wide range. They used the data to test the then widely held view that η is independent of TF and TMS. They found that this widely held view bears little resemblance to the actual behavior of film cooling or film heating systems!

In other words, Papell and Trout demonstrated that η strongly depends on TF and TMS, and that η is a *variable in a nonlinear equation*. Thus they demonstrated that large errors should be expected from correlations such as Eqs (4) and (5) which treat η as a constant coefficient in a linear equation.

On the basis of the experimental results in Papell and Trout, Papell submitted the following discussion on Hartnett, Birkebak, and Eckert (1961):

> *Prior to publication of (Papell and Trout (1959), we) attempted to correlate film cooling using Wieghardt's parameter with limited success. It was found that low temperature, low velocity data similar to that obtained by Wieghardt correlated fairly well but the higher temperature and velocity data fell off considerably. . . .*
>
> *I would like to add a word of caution concerning application of the correlation presented in this paper. The correlation obtained using low temperature and low velocity data is strictly empirical and, as such, its use cannot be extrapolated to higher temperatures and velocities.*

THE EXPERIMENTAL EVIDENCE BY PAPELL AND TROUT (1959) WHICH SUPPORTED THEIR DISSENTING VIEW

Figure 8 in Papell and Trout (1959) contains experimental evidence that η strongly depends on TF and TMS. This figure is reproduced in Appendix 1. Note that the data exhibit excellent internal agreement, and that the effect of TF and TMS on η is first order. For example, Figure 8 indicates that, at $x/s=55$, η may be any value between 0.4 and 0.7, depending on the value of TF/TMS.

Papell and Trout correlated their data on the basis of Eq (7):

$$\eta = f(m)\, f(x/s)\, f(TF/TMS) \qquad (7)$$

They concluded that the data indicated η is proportional to $(TF/TMS)^{0.5}$.

THE CURRENT WIDELY HELD VIEW OF FILM EFFECTIVENESS BEHAVIOR

The current widely held view of film effectiveness behavior agrees with the view expressed by Papell and Trout--namely, that η depends on TF/TMS. Teekaram, Forth, and Jones (1989) summarize the current view of film effectiveness behavior:

> *Many early experiments used a slightly heated injection gas, providing a small temperature difference (and a density ratio of unity). . . Subsequently, it became evident that film-cooling performance depended also on the injection-to-mainstream density ratio, which is far from unity in (a gas turbine) engine due to the large temperature differences. This effect was demonstrated by experiments, e.g. Pedersen et al. (1977) for a single row of holes, and Pai and Whitelaw (1968) for tangential slots . . .*

Similarly, Schwarz, Goldstein, and Eckert (1990) state: "*two parameters of particular importance in film cooling of flat surfaces are the blowing rate and density ratio*".

WIEGHARDT'S (1946) SURPRISING VIEW OF FILM EFFECTIVENESS BEHAVIOR

Because Wieghardt is generally considered the pioneer of film heating and cooling, it is logical to suppose that the early view of film effectiveness behavior was a reflection of his view. For that reason, it is surprising to find the following in Wieghardt (1946):

> *At first, (TAW-TMS) proved to be everywhere proportional to (TF-TMS). This proportionality could be disturbed only at very large temperature differences with considerable density variations . . . In the tests, the density variations of maximum 10 to 20%, however, had no perceptible effect.*

Wieghardt reported the results of film heating tests in which the temperature ratio varied only from 1.10 to 1.17. But he must also have performed tests in which the temperature ratio was outside this range, and these unreported tests must have been the basis for his observation on the lack of proportionality at very large temperature differences.

Wieghardt's statement that proportionality does not hold at very large temperature differences indicates that, if TF/TMS varies over a wide band, η is a variable in a nonlinear equation. This view bears no resemblance to the early view that η is a constant coefficient in a linear equation. In other words, the early view was at odds with the earlier view expressed by Wieghardt!

Wieghardt's view of film effectiveness behavior is essentially the same as the view expressed by Papell and Trout (1959), and the widely held current view, that film effectiveness strongly depends on temperature ratio or density ratio.

WHEN IS η SIMPLE AND DIRECT?

The early view of η held that η is independent of TF and TMS--ie that η is a constant coefficient in the following linear equation:

$$\mathrm{TAW} = \mathrm{TMS} - \eta(\mathrm{TMS} - \mathrm{TF}) \tag{8}$$

When this view accurately describes η behavior over the range of practical interest, the η concept is simple and direct because η completely describes the relationship among TAW, TF, and TMS.

For example, given that η is a constant coefficient in Eq (8), and that its value is 0.3, we may write Eqs (9) and (10):

$$\mathrm{TAW} = \mathrm{TMS} - 0.3(\mathrm{TMS} - \mathrm{TF}) \tag{9}$$

$$(d\mathrm{TAW}/d\mathrm{TF}) = \eta = -(d\mathrm{TAW}/d\mathrm{TMS}) = 0.3 \tag{10}$$

Eq (9) may be used to determine TAW from any values of TF and TMS. Eq (10) may be used to determine the effect of changes in TF and TMS on TAW.

It is important to note that the simplicity of Eqs (9) and (10) results ONLY when η is a constant coefficient in Eq (8). Otherwise, simple equations like (9) and (10) do *NOT* describe film behavior.

In other words, the simplicity of the film effectiveness concept depends on the proportionality noted by Wieghardt:

$$(\mathrm{TMS} - \mathrm{TAW}) \propto (\mathrm{TMS} - \mathrm{TF}) \tag{11}$$

When this proportionality accurately describes film behavior in the range of practical interest, η is simple and direct because the value of η completely describes the relationship among TAW, TF, and TMS.

The experimental results by Hartnett, Birkebak, and Eckert (1961) demonstrated that η is a constant coefficient in Eq (8) if TMS is 90 F and TF is in the range 100 to 240 F. If these test conditions include the range of practical interest, or if η results may be confidently extrapolated far beyond the test range, then the η concept is simple and direct.

WHEN IS η NOT SIMPLE AND DIRECT?

The η parameter is *NOT* simple and direct if η is dependent on TF and TMS. This dependence means that η is a variable in the following nonlinear equation:

$$\mathrm{TAW} = \mathrm{TMS} - \eta(\mathrm{TF},\mathrm{TMS})(\mathrm{TMS} - \mathrm{TF}) \tag{12}$$

Due to the nonlinearity, η results may *NOT* be confidently extrapolated far beyond the test range.

It is important to note that Eq (12) is mathematically undesirable. This may be noted by observing that Eq (12) is *identical* to Eq (13), and Eq (13) is *exactly* analogous to Eq (14).

$$(\mathrm{TMS} - \mathrm{TAW}) = \frac{(\mathrm{TMS} - \mathrm{TAW})}{(\mathrm{TMS} - \mathrm{TF})}(\mathrm{TMS} - \mathrm{TF}) \tag{13}$$

$$y = \frac{y}{x}\,x \tag{14}$$

Eq (14) is mathematically undesirable because y is on both sides of the equation--ie y and x are not separated. Notice that (y/x) is the mathematical analog of η. This analog reveals what is wrong with η when it is a variable in Eq (12)--η is the ratio of the dependent variable (TMS−TAW) to the independent variable (TMS−TF)! Therefore a variable η makes it IMPOSSIBLE to separate the independent and dependent temperature variables--IMPOSSIBLE to think or to write equations in the mathematically desirable form of Eq (15):

$$y = f(x) \tag{15}$$

Modern mathematics has no use for equations such as Eqs (12) to (14) in which dependent and independent variables are combined rather than separated. In modern mathematics, the variables are separated whenever possible because separation greatly simplifies the solution of problems. The combined/undesirable form of Eq (12) is readily transformed to the separated/desirable form of Eq (15), but *ONLY by eliminating* η.

In summary, η is not simple or direct when it is a variable which depends on TF and TMS. This may be seen by solving the following simple problem:

> **Given that the mainstream temperature is 1500 R and the film effectiveness is described by Eq (16), what film temperature would result in an adiabatic wall temperature of 1200 R?**

$$\eta = 0.57(\mathrm{TF}/\mathrm{TMS})^{0.5} \tag{16}$$

Notice that this simple problem must be solved in an *indirect* manner unless η is eliminated from the equation.

THE CURRENT WAY TO DESCRIBE TAW WHEN η DEPENDS ON TF AND TMS

The widely accepted current way to describe TAW hen η depends on TF and TMS is the same as that utilized by Papell and Trout (1959). The method is described by the following:

- Define η to be (TMS-TAW)/(TMS-TF).
- Assume/deduce that film cooling behavior depends on TF/TMS rather than TF and TMS taken separately.
- Reduce film cooling (or film heating) temperature data to the dimensionless groups η and TF/TMS.
- From the reduced data, generate a correlation in the form η(TF/TMS, x/s, m, etc.).
- Determine TAW in design applications from the correlation and the definition of η, Eq (1).

A NEW AND MATHEMATICALLY DESIRABLE WAY TO DESCRIBE TAW WHEN η DEPENDS ON TF AND TMS

As noted previously, the above methodology is mathematically undesirable when η is a variable which depends on TF and TMS--ie when (TMS–TAW) is a nonlinear function of (TMS–TF). In this case, a mathematically desirable method is as follows:

- Assume/deduce that film cooling behavior depends on TF/TMS rather than TF and TMS taken separately.
- Reduce film cooling (or film heating) data to the dimensionless groups TAW/TMS and TF/TMS.
- From the reduced data, generate a correlation in the form (TAW/TMS)(TF/TMS, x/s, m, etc.).
- Determine TAW in design applications from the correlation and

$$TAW = (TAW/TMS)TMS$$

ATA REDUCTION/CORRELATION--NEW VS CURRENT CONCEPT

Now let us compare the current method vs the new method by using both methods to reduce and correlate the data set Papell and Trout (1959) used to prepare the graphical correlation in their Figure (9c) (shown in Appendix 1). The data were originally presented in graphical form, and have been converted to the digital data set in Table (1).

Using current methodology, the data set in Table (1) is reduced to values of η by substituting the temperature data into Eq (1). The reduced data are listed in Table (2), and are correlated in Figure (1) in the form η(x/s) with parameter TF/TMS.

Using new methodology, the data set in Table (1) is reduced to values of TAW/TMS. The reduced data are listed in Table (3), and are correlated in Figure (2) in the form (TAW/TMS)(x/s) with parameter TF/TMS.

CONCEPTUAL SIMPLICITY--NEW VS CURRENT CONCEPT

The purpose of the η concept is to describe the relationship among TAW, TF, and TMS in a simple and useful way. Let us determine this relationship from the experiment by Papell and Trout (1959), applying both current and new concepts.

Figure (3) uses current methodology to describe the relationship among TAW, TF, and TMS. Notice that η is everywhere a monotonic and well behaved function of TF/TMS.

But note that the designer's real interest is not in how η responds to TF/TMS--his real interest 's in how *TAW* responds to TF and TMS. That Fig. 3) does not address the designer's real interest can be seen by solving the following problem:

By inspection of Figure 3, qualitatively describe how TAW responds to TF at an arbitrary TMS.

Figure 4 presents the same information as Figure 3, but in the new form (TAW/TMS)(TF/TMS) instead of the current form ((TMS-TAW)/(TMS-TF))(TF/TMS). Figure 4 indicates that, at an arbitrary TMS, TAW is a highly nonlinear function of TF--so highly nonlinear that the correlation describes a broad region in which TAW *INcreases* as TF *DEcreases*!!!

It is essential to note that Figures 3 and 4 describe exactly the same behavior--they differ only in form. Figure (3) is in a form which is largely unintelligible because the independent and dependent variables are combined in η. Figure (4) is in a form which is readily intelligible because the independent and dependent variables are separated. Note that this readily intelligible form could be realized *ONLY* by abandoning η.

Notice that the solution based on Fig. (4) is so simple that the problem can hardly be considered a problem. And of course the point to be made is that the new methodology readily reveals functionality among design parameters. It would be possible to determine this same functionality using the current methodology and Figure 3, but it would require much more effort, and would involve a much greater likelihood of error.

The purpose of concepts is to order experience in the simplest possible way. Therefore the best concepts are those which are simplest.

SIMPLICITY OF APPLICATION--NEW VS CURRENT CONCEPT

It is important to note that the difference between the new and the current concept is a matter of form, not substance. The two concepts result in correlations which are different in appearance, but which describe exactly the same behavior. (In fact, as shown below, the two forms are readily transformed to each other.) Therefore the relative merit of new vs current concept must be decided on the bases of simplicity of application and likelihood of error.

Now compare Figures (1) and (2), bearing in mind that each figure is a graphical correlation of the *same* data set, and that the sole purpose of each figure is to describe how TAW is related to TF and TMS over a range of x/s values. Note the following:

- Figure 2 describes TAW directly and explicitly in TAW/TMS. Figure 1 describes TAW indirectly and implicitly in η. It is self evident that a direct and explicit method is better than a method which is indirect and implicit.
- Figure (2) readily reveals how TAW is related to TF and TMS. Figure (1) does not. Both figures indicate that lowering TF/TMS from .571 to .368 has *no effect* on TAW if x/s is greater than 15. Note that this is impossible to see by inspection of Figure 1, whereas this is readily apparent by inspection of Figure 2.
- Figure 2 is an effective design tool because it readily reveals functionality among design parameters, whereas Figure 1 does not.
- Using Figure (1), an iterative method is required *SIMPLY TO READ THE FIGURE* if TMS and TAW are given, and TF is desired. This may be seen by solving the following simple problem:

> **Given that (x/s)=10 and TMS=2000 R, use the correlation in Figure (1) to determine the TF which would result in TAW=1200 R. Repeat using the correlation in Figure (2).**

Notice that this problem is solved *iteratively* if Figure (1) is used, and *by inspection* if Figure (2) is used!

In summary, the new method based on TAW/TMS is much simpler to apply than the current method based on η. Therefore it is less likely to result in design error.

THE CONCEPTUAL AND PRACTICAL DIFFERENCES BETWEEN THE NEW AND CURRENT METHODS

The conceptual difference between the new and current methods is that the parameters in the current method are viewed as "temperature ratio" and "effectiveness", whereas the parameters in the new method may be viewed as dimensionless temperatures, or as normalized temperatures, or as temperature ratios. (Notice that, in the new method, the temperatures are nondimensionalized by normalization to TMS, and thus the dimensionless mainstream temperature is unity.)

The practical difference between the new and current methods is that data reduction and correlation, and equipment design and analysis, are based on TAW/TMS rather than (TMS-TAW)/(TMS-TF).

HOW TO TRANSFORM CORRELATIONS FROM η TO (TAW/TMS)

The transformation of correlations from η to TAW/TMS is readily accomplished as follows:

- Replace η with (TMS–TAW)/(TMS–TF).
- Divide by TMS in order to normalize the temperatures to TMS.
- Separate the independent and dependent variables--ie arrange the equation so that all terms containing TAW/TMS are on one side, and all terms containing TF/TMS are on the other.

For example, Eq (17) is a film effectiveness correlation proposed by Papell and Trout (1959):

$$\eta = 12.6(m)(s/x)^{0.72}(TF/TMS)^{0.5} \qquad (17)$$

Substituting for η, we obtain Eq (18). Dividing by TMS and then separating TAW/TMS and TF/TMS, we obtain Eq (19). Eq (19) is the result of transforming Eq (17) into the new form.

$$(TMS-TAW)/(TMS-TF) = 12.6(m)(s/x)^{.72}(TF/TMS)^{.5} \qquad (18)$$

$$(TAW/TMS) = 1-12.6(m)(s/x)^{.72}(TF/TMS)^{.5}(1-TF/TMS) \qquad (19)$$

ABANDONING FILM EFFECTIVENESS

The film effectiveness concept has been used on a universal scale for 50 years, and it may be many years before η is altogether abandoned in those industries in which it is a variable rather than a constant coefficient. However, conversion from the current method to the new method is so simple that worldwide conversion could be accomplished in a few years by proper utilization of the engineering media.

CONCLUSIONS

- The film effectiveness concept is simple and direct only if η is independent of TF and TMS--only if η is a constant coefficient in a linear equation.
- Literature data indicate that η is essentially independent of TF and TMS only if TF/TMS lies within a narrow band of perhaps 20 or 30%.
- Literature data indicate that, if the TF/TMS values of practical interest cover a range greater than 20 or 30%, η is dependent on TF and TMS, in which case η is a variable in a nonlinear equation.
- When η is a variable in a nonlinear equation, it prevents separation of dependent and independent variables, and thereby complicates and confuses the solution of practical problems. In this event, the film effectiveness concept should be abandoned.
- The new concept presented herein is simple and direct even if TF/TMS varies over an infinite range.
- The TF/TMS values of practical interest in the gas turbine industry cover a range much larger than 20 to 30%. Therefore the gas turbine industry should abandon the film effectiveness concept in favor of the new concept presented herein.

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NOMENCLATURE

$f(x,y,z)$	unspecified function of x, y, and z
m	ratio of film mass flow rate to mainstream mass flow rate
TAW	adiabatic wall temperature (absolute)
TF	film coolant temperature (absolute)
TMS	mainstream temperature (absolute)
x, y	arbitrary variables
x/s	ratio of distance from film injection point to height of injection duct
η	film effectiveness defined by Eq (1)

TABLE 1

DATA SET USED BY PAPELL AND TROUT TO PREPARE THEIR FIGURE (9c)

TF, R	555	862
TMS, R	1510	1510
s, in	0.5	0.5
Mach No.	0.23	0.20
m	0.50	0.49

x/s	TAW, R	TAW, R
0	783	990
5	860	1003
9	918	1016
13	1044	1062
17	1132	1140
21	1190	1185
25	1219	1231
31	1258	1276
37	1287	1302
43	1306	1322
49	1316	1322
68	1345	1348

TABLE 2

REDUCED FORM OF DATA SET IN TABLE 1-- CURRENT METHODOLOGY

TF/TMS	0.368	0.571
s, in	0.50	0.50
Mach No.	0.23	0.20
m	0.50	0.49

x/s	η	η
0	.76	.80
5	.68	.78
9	.62	.76
13	.49	.69
17	.40	.57
21	.34	.50
25	.30	.43
31	.26	.36
37	.23	.32
43	.21	.29
49	.20	.29
68	.17	.25

TABLE 3

REDUCED FORM OF DATA SET IN TABLE 1-- NEW METHODOLOGY

TF/TMS	0.368	0.571
s, in	0.50	0.50
Mach No.	0.23	0.20
m	0.50	0.49

x/s	TAW/TMS	TAW/TMS
0	.52	.66
5	.57	.66
9	.61	.67
13	.69	.70
17	.75	.75
21	.79	.79
25	.81	.82
31	.83	.85
37	.85	.86
43	.86	.88
49	.87	.88
68	.89	.89

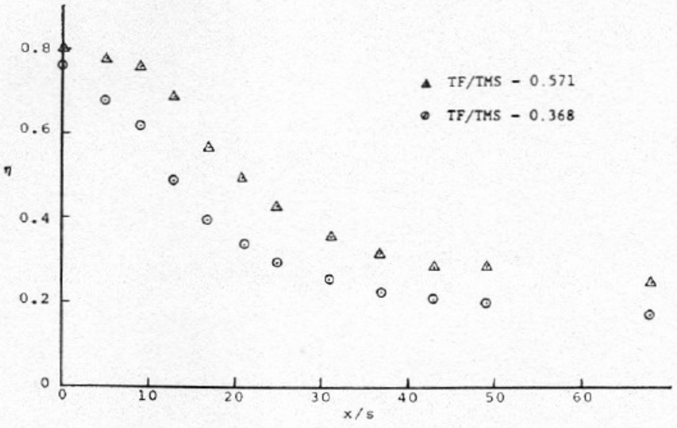

FIGURE 1 CORRELATION OF DATA IN TABLE 1--CURRENT METHODOLOGY

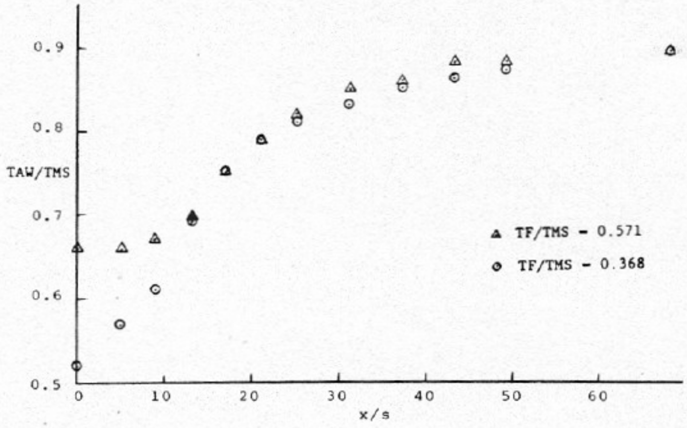

FIGURE 2 CORRELATION OF DATA IN TABLE 1--NEW METHODOLOGY

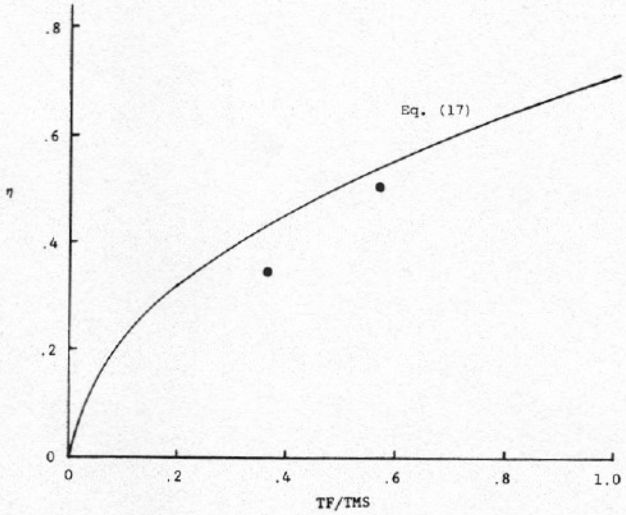

FIGURE 3 THE RELATIONSHIP AMONG ADIABATIC WALL, FILM, AND MAINSTREAM TEMPERATURES AT m=0.50 AND x/s=21--CURRENT METHODOLOGY

(Data points and Eq. (17) are from Papell and Trout (1959).)

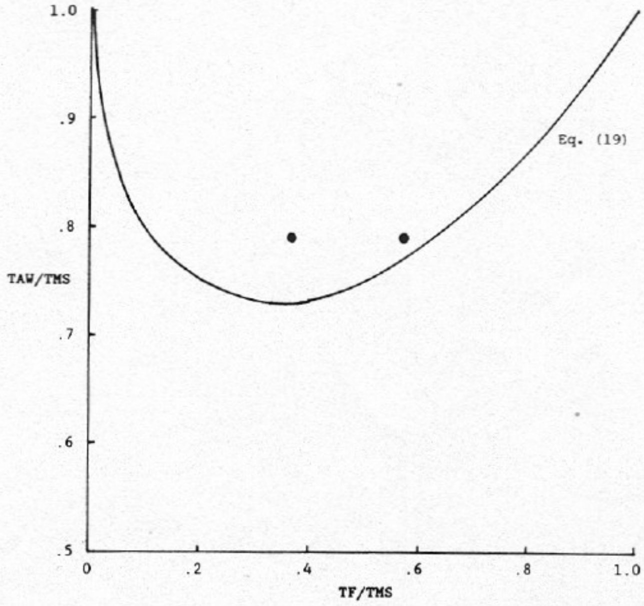

FIGURE 4 THE RELATIONSHIP AMONG ADIABATIC WALL, FILM, AND MAINSTREAM TEMPERATURES AT m=0.50 AND x/s=21--NEW METHODOLOGY

(Data points are from Papell and Trout (1959). Eq. (19) is tranformation of Eq. (17) from Papell and Trout.)

APPENDIX 1 FIGURES 8 AND 9 BY PAPELL AND TROUT (1959)

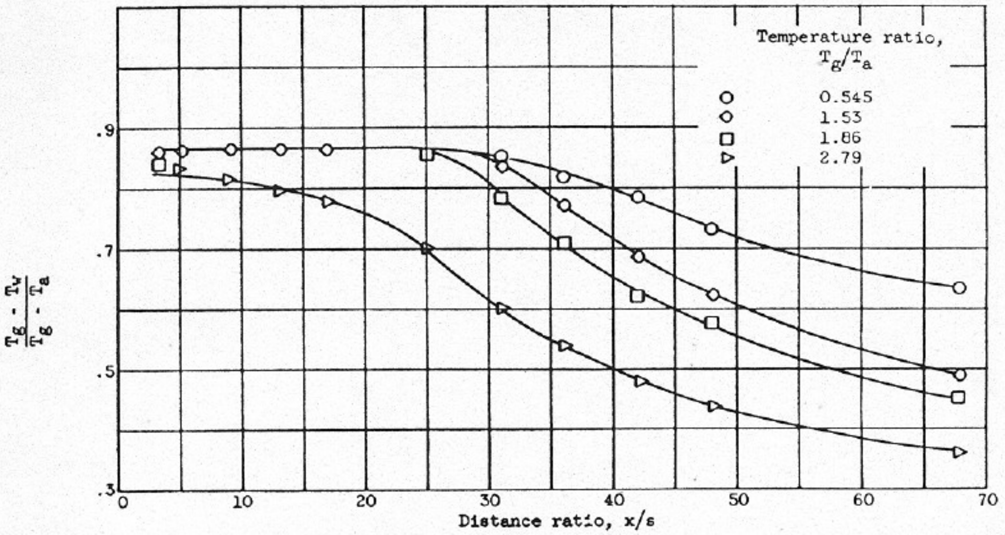

Figure 8. - Temperature-ratio effect on film cooling at constant values of mainstream Mach number of 0.5, slot height of one-half inch, and specific weight flow ratio of 1.00.

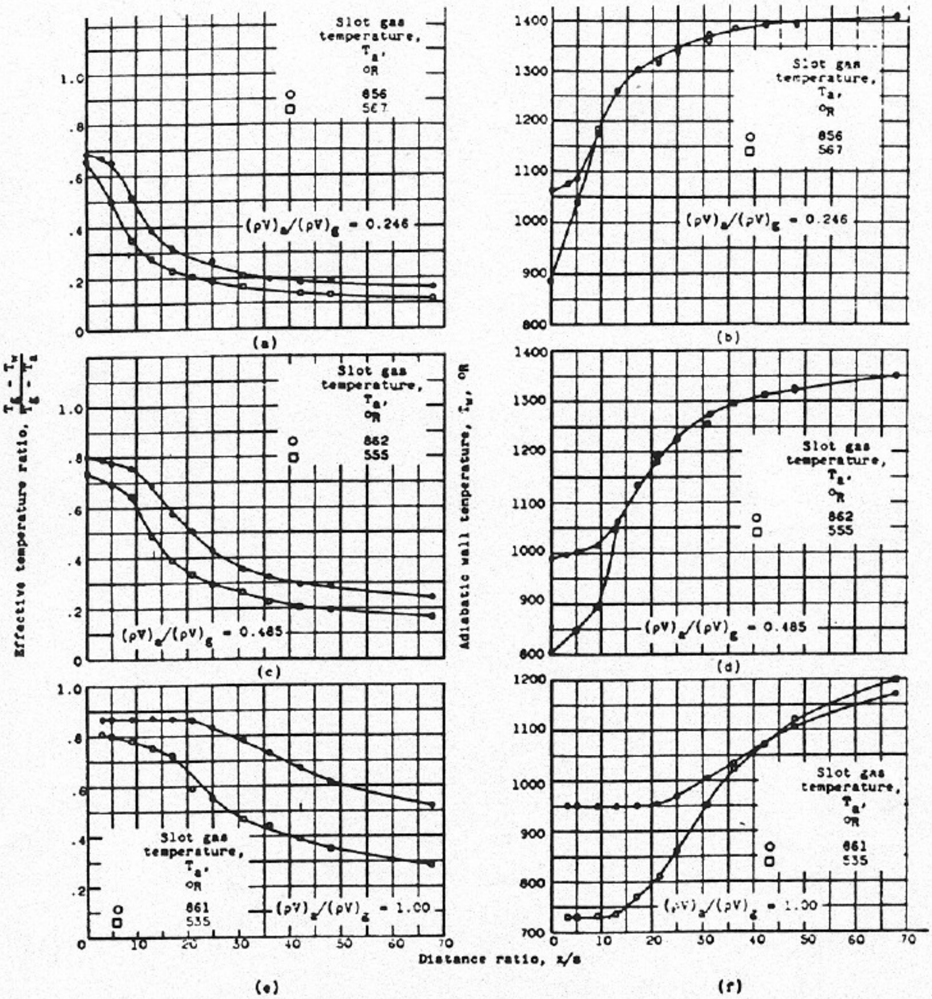

Figure 9. - Effect of cooling-air temperature level on effective temperature ratio and wall temperature at constant value of mainstream gas Mach number of 0.23, slot height of one-half inch, and mainstream gas temperature of 1510° R.