THE HIGHLY NONLINEAR THERMAL BEHAVIOR OF FILM COOLING

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ABSTRACT

The current view of film cooling/heating behavior is largely the result of room temperature experiments in which the high temperatures typical of gas turbines were only simulated. The simulation rests on the assumption/deduction that the effect of temperature on film cooling behavior is due solely to the effect of temperature on fluid density.

A few experiments reported in the literature have included wide variation in temperature. In this article, the data from several of these are examined in order to determine the actual, observed effect of temperature on film cooling behavior.

Literature data exhibit a highly linear relationship between T_{aw} and T_{fc} when the film is injected through a slot, and T_{fc}/T_{ms} lies in the range 0.8 to 1.27. The data also indicate that this relationship is highly nonlinear when T_{fc}/T_{ms} is less than approximately 0.8. The nonlinearity is so pronounced that T_{aw} may not decrease even though (T_{fc}/T_{ms}) is decreased from 0.57 to 0.35.

Nonlinearity in the relationship between T_{aw} and T_{fc} has a major impact on optimum system design whenever the thermal designer has design control over the film coolant temperature.

NOMENCLATURE

M	Coolant-to-mainstream mass flux ratio evaluated at the film hole exit; often called blowing ratio.
s	Slot height.
T_{aw}	Adiabatic wall temperature.
$T_{aw}[T_{fc}]$	Denotes that T_{aw} depends in part on T_{fc}.
T_{fc}	Film coolant temperature.
T_{ms}	Mainstream temperature.
x	Distance from film slot.
η	Film effectiveness defined by Equation (1).
η_{ind}	ind indicates η is independent of T_{fc} and T_{ms}.
$\eta[T_{fc}/T_{ms}]$	Bracket indicates η depends in part on T_{fc}/T_{ms}.

$\eta[T_{fc},T_{ms}]$ Bracket indicates η depends in part on T_{fc} and T_{ms}.

INTRODUCTION

For several decades, it has been widely assumed or deduced that the effect of T_{fc} and T_{ms} on film cooling behavior results solely from the temperature effect on fluid density. Because of this view, film cooling/heating experiments are generally performed at near room temperature, using fluids of different density to simulate the T_{fc} and T_{ms} values of interest.

Eckert (1992) notes:

> *. . . our present ability to predict the thermal performance of film cooling arrangements used to protect the hot components of gas turbines (is based on) information usually obtained by model experiments carried out at near room temperature as opposed to the high temperature encountered in the gas turbines.*

The end result of this experiment methodology is that the current view of the effect of T_{fc} and T_{ms} on film cooling behavior is based largely on assumption and/or deduction.

In this article, the effect of T_{fc} and T_{ms} on film cooling behavior is determined from the small number of experiments which established their effect empirically, rather than by simulation and assumption/deduction.

WIEGHARDT'S VIEW OF FILM EFFECTIVENESS

Film cooling/heating was pioneered by Wieghardt (1946) whose interest was film heating for aircraft deicing. Wieghardt noted that, over the range of interest for deicing, the ratio $(T_{ms}-T_{aw})/(T_{ms}-T_{fc})$ is independent of T_{fc} and T_{ms}. He therefore correlated his data based on an η parameter defined by Eq. (1).

$$\eta_{ind} = (T_{ms} - T_{aw})/(T_{ms} - T_{fc}) \qquad (1)$$

(The subscript ind denotes that η is independent of T_{fc} and T_{ms}. The subscript is needed in order to distinguish between Wieghardt's view which prevailed for several decades, and the current view that film cooling behavior is dependent on T_{fc}/T_{ms}.)

Wieghardt intended the η parameter to be used to estimate T_{aw} from Equation (2). (Eq. (2) is obtained by rearranging Eq. (1)).

$$T_{aw} = T_{ms} - \eta_{ind}(T_{ms} - T_{fc}) \qquad (2)$$

Note that, because η is independent of T_{fc} and T_{ms}, Eq. (2) is linear, and η_{ind} is a constant coefficient in the equation. Conversely, if η were dependent on T_{fc} and/or T_{ms}, Eq. (2) would be nonlinear, and η would be a contrived and unnecessary variable in the equation.

The linear view of the relationship between T_{aw} and T_{fc} is reflected in Wieghardt's correlating form

$$\eta_{ind} = f[x/Ms] \qquad (3)$$

which states that η is dependent on x/Ms, and is independent of T_{fc} and T_{ms}.

THE EXPERIMENTAL IMPACT OF WIEGHARDT'S VIEW

Wieghardt's view that η is independent of T_{fc} and T_{ms} prevailed throughout the 1940's, 50's, and 60's. In light of this view, there was no need to vary T_{fc} or T_{ms} in film cooling experiments. Consequently film cooling experiments were generally performed with the mainstream at essentially ambient temperature, and the film fluid slightly above or slightly below ambient. Since the same fluid was used for film and for mainstream, the temperature ratio and the density ratio were both essentially unity.

The following by Seban (1960) reflects the widely held view of the 1940's, 50's, and 60's that η is independent of T_{fc} and T_{ms}:

> *. . . the effect of 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.*

Seban's description of his experiment indicates that it was in fact designed in accordance with this view:

> *. . . 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.*

Goldstein's (1971) comprehensive and often cited review presents many film cooling/heating correlations taken from the literature of the 1940's, 50's, and 60's. Without exception, the correlations indicate that η is independent of T_{fc} and T_{ms}--i.e. that the relationship between T_{aw} and $(T_{ms}-T_{fc})$ is linear.

THE CURRENT VIEW OF EFFECTIVENESS

In the current view, η depends in part on the value of the temperature ratio T_{fc}/T_{ms}. Therefore Eq. (2) should be written in the form

$$T_{aw} = T_{ms} - \eta[T_{fc}/T_{ms}](T_{ms} - T_{fc}) \quad (4)$$

to denote the following: η depends in part on T_{fc}/T_{ms}; Eq. (4) is nonlinear; η is a variable in the equation.

It is important to recognize that the current view is not completely general. A general view would consider that η depends in part on the individual values of T_{fc} and T_{ms}, in which case Eq. (4) would be written

$$T_{aw} = T_{ms} - \eta[T_{fc},T_{ms}](T_{ms} - T_{fc}) \quad (5)$$

Thus the current view represents a definite conclusion about film cooling behavior, just as the view that η is independent of T_{fc} and T_{ms} represents a definite conclusion.

(Adiutori (1991) notes that, when η is dependent on T_{fc}/T_{ms} (as in the current view), $\eta[T_{fc}/T_{ms}]$ is mathematically unacceptable, and should be abandoned in favor of the parameter $(T_{aw}/T_{ms})[T_{fc}/T_{ms}]$.

The difference in the two parameters is a matter of form and not substance--i.e. $(T_{aw}/T_{ms})[T_{fc}/T_{ms}]$ is more revealing and simpler to apply, but the same results can be obtained from the form $\eta[T_{fc}/T_{ms}]$.)

THE BASIS FOR THE CURRENT VIEW

Teekaram et al (1989) describe the basis for the current temperature (density) ratio view of film cooling thermal 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 . . .*

It is important to note that the experiments cited by Teekaram et al (1968) did not directly establish the effect of T_{fc} and T_{ms} on film cooling behavior, since they did not include wide variation in T_{fc} and T_{ms}. In the cited experiments, variation in fluid density was used to simulate variation in T_{fc} and T_{ms}. The effect of variation in T_{fc} and T_{ms} was then deduced from the observed effect of density variation, and the assumption/deduction that the effect of temperature on film cooling behavior is due solely to the temperature effect on fluid density.

THE NEED FOR EXPERIMENTS WITH ACTUAL VARIATION IN TEMPERATURE

Because the current view of the relationship between η and T_{fc} and T_{ms} is based on simulation and deduction which are open to question, it would be highly desirable to determine this relationship from experiments which included actual variation in T_{fc} and T_{ms}. It would also be desirable that the experiments be steady-state in order that the data reduction would be so simple as to require no questionable deduction.

Unfortunately, as noted above by Eckert, most film cooling experiments reported in the literature contain little variation in T_{fc} or T_{ms}. Among the exceptions are the film heating experiment by Hartnett et al (1961), and the film cooling experiment by Papell and Trout (1959). The data from these experiments contain considerable variation in T_{fc} and/or T_{ms}, and the data are steady-state.

These data are used below to induce the relationship between T_{aw}, T_{fc}, and T_{ms}, based on the current view that film cooling behavior depends on T_{fc}/T_{ms} rather than the individual values of T_{fc} and T_{ms}.

THE EFFECT OF T_{fc} ON T_{aw}--INDUCED FROM FILM HEATING DATA REPORTED BY HARTNETT ET AL (1961)

Hartnett et al (1961) reported data obtained in a film heating experiment in which the test matrix included considerable variation in T_{fc}, but no variation in T_{ms}. The experiment was performed in a wind tunnel at the following conditions:

- Blowing ratio = 0.28.
- Slot height = 0.123 inches.
- Mach number = 0.15.
- Mainstream air temp. = 530 R.
- Film cooled region: flat plate.
- Film coolant temperature = 540 to 674 R.

The authors presented their film heating data in the form $\eta[x/ms]$ with $(T_{fc}-T_{ms})$ parameter, and fixed M, s, T_{ms}, and Mach number.

The data reported by Hartnett et al is presented in Figure (1) in the form $T_{aw}[T_{fc}]$, with x/s parameter, and fixed values of M, s, T_{ms}, and Mach number. Note that the curves in Fig. (1) necessarily converge on the point $T_{aw}=T_{fc}=T_{ms}$ because, when it is true that $T_{fc}=T_{ms}$, it is also true that $T_{aw} = T_{ms}$.

Figure (1) indicates that, for M=.28, (x/s)<84, Mach No.=.15, T_{ms}=530 R, and T_{fc}=540 to 674 R:

- The relationship between T_{aw} and T_{fc} is linear--i.e. is described by an equation of the form

$$T_{aw} = 530 - \eta(530 - T_{fc}) \qquad (6)$$

- The linearity in the relationship between T_{aw} and T_{fc} indicates that η is independent of T_{fc}.
- In light of the current view that film cooling behavior depends on T_{fc}/T_{ms}, the fact that η is independent of T_{fc} demonstrates

that η is independent of T_{ms}. Therefore Eq. (6) may be written in the more general form of Eq. (7), and Eq. (7) may be said to apply over the T_{fc}/T_{ms} range covered in the experiment (1.0 to 1.27).

$$T_{aw} = T_{ms} - \eta_{ind}(T_{ms} - T_{fc}) \quad (7)$$

It should be noted that the above results based on data by Hartnett et al (1961) agree with the results by Wieghardt (1946)--i.e. the data from both experiments support the conclusions that η is independent of T_{fc} and T_{ms}, and that film heating behavior is described by a linear equation in the form of Eq. (2) (or equally Eq. (6)).

THE EFFECT OF T_{fc} ON T_{aw}--INDUCED FROM FILM COOLING DATA REPORTED BY PAPELL AND TROUT (1959)

Papell and Trout (1959) reported data obtained in a film cooling experiment in which the fluid was injected through a slot, and the test matrix included considerable variation in both T_{ms} and T_{fc}. The experiment was performed in a wind tunnel at the following conditions:

- Mach number: 0.2 to 0.7.
- Blowing ratio: 0 to 5.
- Slot height: 1/16 to 1/2 inch.
- Mainstream: Air at 500 to 1500 R.
- Film: Air at 550 to 950 R

The authors present their data in the form $\eta[x/s]$, with M parameter, and fixed values of T_{fc}, T_{ms}, s, and Mach number.

Figures (2) and (3) present a small fraction of the data reported in Papell and Trout. Note that the data cover a very wide range of parameters, and are presented in the dimensional form $T_{aw}[T_{fc}]$, with x/s parameter, and with fixed values of M, s, T_{ms}, and Mach number. Also note that the curves in Figures (2) and (3) converge on the point $T_{aw}=T_{fc}=T_{ms}$, just as the curves in Figure (1) did, and for the same reason.

Figures (2) and (3) indicate that $T_{aw}[T_{fc}]$ is highly nonlinear. Note that $T_{aw}[T_{fc}]$ is so highly nonlinear that, over much of the film cooled region, T_{aw} failed to decrease even though T_{fc} decreased from 860 to 540 R. And at several locations, T_{aw} actually INcreased as T_{fc} DEcreased!

In summary, Figures (2) and (3) demonstrate that the film cooling data reported in Papell and Trout indicate the following at M = .2 to 1.0, s = .5 inches, $(x/s) < 70$, $T_{ms} = 1510$ R, $T_{fc} = 500$ to 1500 R, Mach number = 0.2 to 0.5:

- The effect of T_{fc} on T_{aw} is highly nonlinear--so nonlinear that decreases in T_{fc} oftentimes have no effect on T_{aw}, and sometimes cause an increase in T_{aw}.
- The highly nonlinear relationship between T_{aw} and T_{fc} demonstrates that η strongly depends on T_{fc}. In light of the current view that film cooling behavior depends on T_{fc}/T_{ms}, this conclusion can be generalized to the conclusion that η strongly depends on T_{fc}/T_{ms}.
- Because η oftentimes depends in part on T_{fc}/T_{ms}, film cooling behavior is not generally described by the linear Eq. (2). It is generally described by the nonlinear Eq. (4) (or the nonlinear Eq. (5), if in fact film cooling behavior depends on the individual values of T_{fc} and T_{ms} rather than their ratio).

$T_{aw}[T_{fc}]$ IN DIMENSIONLESS FORM

In order to combine the film heating results by Hartnett et al (1961) with the film cooling results by Papell and Trout (1959), it is necessary to transform the results to dimensionless form. The transformation could be to the form $\eta[T_{fc}/T_{ms}]$, or to the form $(T_{aw}/T_{ms})[T_{fc}/T_{ms}]$.

The latter form better describes the relationship between T_{aw} and T_{fc} because T_{aw}/T_{ms} is proportional to T_{aw}, and T_{fc}/T_{ms} is proportional to T_{fc}. (Note that the conventional form $\eta[T_{fc}/T_{ms}]$ tends to conceal the relationship between T_{aw} and T_{fc} because η is not proportional to T_{aw}.)

Figure (4) is the dimensionless transformation of the Hartnett et al data in Figure (1), and the Papell and Trout data (for a Mach number of 0.22) in Figure (2). Note that Figure (4) is in the dimensionless form $(T_{aw}/T_{ms})[T_{fc}/T_{ms}]$.

Figure (4) indicates that the two sets of data are in agreement in that together they describe well-behaved curves, demonstrating that they do in fact describe different regions of the same overall behavior. Also notice that Figure (4) indicates that the relationship between T_{aw} and T_{fc} is:

- Highly linear when T_{fc}/T_{ms} is in the range 0.8 to 1.27.
- Highly nonlinear when T_{fc}/T_{ms} is less than approximately 0.8.

THE PRACTICAL IMPACT OF THE HIGHLY NONLINEAR BEHAVIOR OF $T_{aw}[T_{fc}]$

In practical situations, the film cooling system thermal designer generally has no design control over T_{ms}. However, he oftentimes has considerable design control over T_{fc}. For example, the thermal designer may determine whether a film coolant cooler will be provided to lower T_{fc} in order to attain the required T_{aw}. Or he may select the compressor stage from which the film fluid is to be extracted.

It is almost always true that improved cooling will result from lowering the coolant temperature. If a film cooling system thermal designer holds the understandable view that improved film cooling will necessarily result from lowering T_{fc}, and if he has design control over T_{fc}, then there is a strong likelihood that the system design will be less than optimum if it exhibits the thermal behavior described in Figure (4).

For example, given a film cooling system in which T_{aw} at a critical location is above the acceptable limit, the thermal designer might decide to lower T_{aw} at that location by installing a film coolant cooler which would lower T_{fc}/T_{ms} from 0.6 to 0.4. If the system behaved as described in Figure (4), lowering T_{fc}/T_{ms} from 0.6 to 0.4 would have no effect on T_{aw} over much of the film cooled region. Therefore installing the film fluid cooler would likely *NOT* decrease T_{aw} at the critical location, and the parasitic effect of the cooler would negatively impact gas turbine performance.

In summary, optimum film cooling system design can result only if the designer is consciously aware that the relationship between T_{aw} and T_{fc} may be highly nonlinear--so nonlinear that decreasing the value of T_{fc} may not result in a decreased value of T_{aw}. One way to increase this awareness is to describe highly nonlinear film cooling behavior in the revealing form $(T_{aw}/T_{ms})[T_{fc}/T_{ms}]$ in place of the form $\eta[T_{fc}/T_{ms}]$.

SUMMARY OF CONCLUSIONS

Based on the current view that film cooling/heating depends on the value of

T_{fc}/T_{ms} rather than the individual values of T_{fc} and T_{ms}, film heating data by Hartnett et al (1961), and film cooling data by Papell and Trout (1959) indicate the following:

- The relationship between T_{aw} and T_{fc} is highly linear when the film is injected through a slot, and T_{fc}/T_{ms} is in the range 0.8 to 1.27.
- The relationship between T_{aw} and T_{fc} is highly nonlinear when the film is injected through a slot, and T_{fc}/T_{ms} is in the range 0.35 to 0.8. The nonlinearity may be so highly pronounced that T_{aw} fails to decrease even though T_{fc} is decreased from 0.57 to 0.35.
- Nonlinearity in the relationship between T_{aw} and T_{fc} is of particular practical importance whenever the thermal designer has design control over T_{fc}.

The highly nonlinear thermal behavior observed by Papell and Trout (1959) was the result of a comprehensive experiment performed in a world class laboratory. Therefore, although this experiment does not by itself establish that film cooling generally exhibits highly nonlinear thermal behavior, it does establish that such behavior can and does occur.

REFERENCES

Adiutori, E. F., 1991, "A New and Simple Concept to Replace Film Effectiveness", ASME Paper No. 91-GT-394

Eckert, E. R. G., 1992, "Similarity Analysis of Model Experiments for Film Cooling in Gas Turbines", *Warme- und Stoffubertragung*, Vol. 27, pp 217-223

Goldstein, R.J., 1971, "Film Cooling", *Advances in Heat Transfer"*, Academic Press

Hartnett, J. P., Birkebak, R. C., and Eckert, E. R. G., 1961, "Velocity Distributions, Effectiveness and Heat Transfer for Air Injected Through a Tangential Slot into a Turbulent Boundary Layer", ASME *Journal of Heat Transfer*, August

Papell, S., and Trout, A. M., 1959, "Experimental Investigation of Air Film Cooling Applied to an Adiabatic Wall by Means of an Axially Discharging Slot", NASA TN D-9

Pai, B. R., and Whitelaw, J. H., 1968, "The Influence of Density Gradients on the Effectiveness of Film-Cooling", *ARC Conference Proceedings 1013*

Pedersen, D. R., Eckert, E. R. G., and Goldstein, R. J., 1977, "Film-Cooling with Large Density Differences Between the Mainstream and Secondary Fluid Measured by the Heat-Mass Transfer Analogy", ASME *Journal of Heat Transfer*, Vol. 99, November

Seban, R. A., 1960, "Heat Transfer and Effectiveness for a Turbulent Boundary Layer with Tangential Fluid Injection", ASME *Journal of Heat Transfer*, November

Teekaram, A. J. H., Forth, C. J. P., and Jones, T. V., 1989, "The Use of Foreign Gas to Simulate the Effects of Density Ratios in Film Cooling", ASME *Journal of Turbomachinery*, Vol. 111, January

Wieghardt, K., 1946, "Hot Air Discharge for De-Icing", AAF Translation, No. F-TS-919 RE

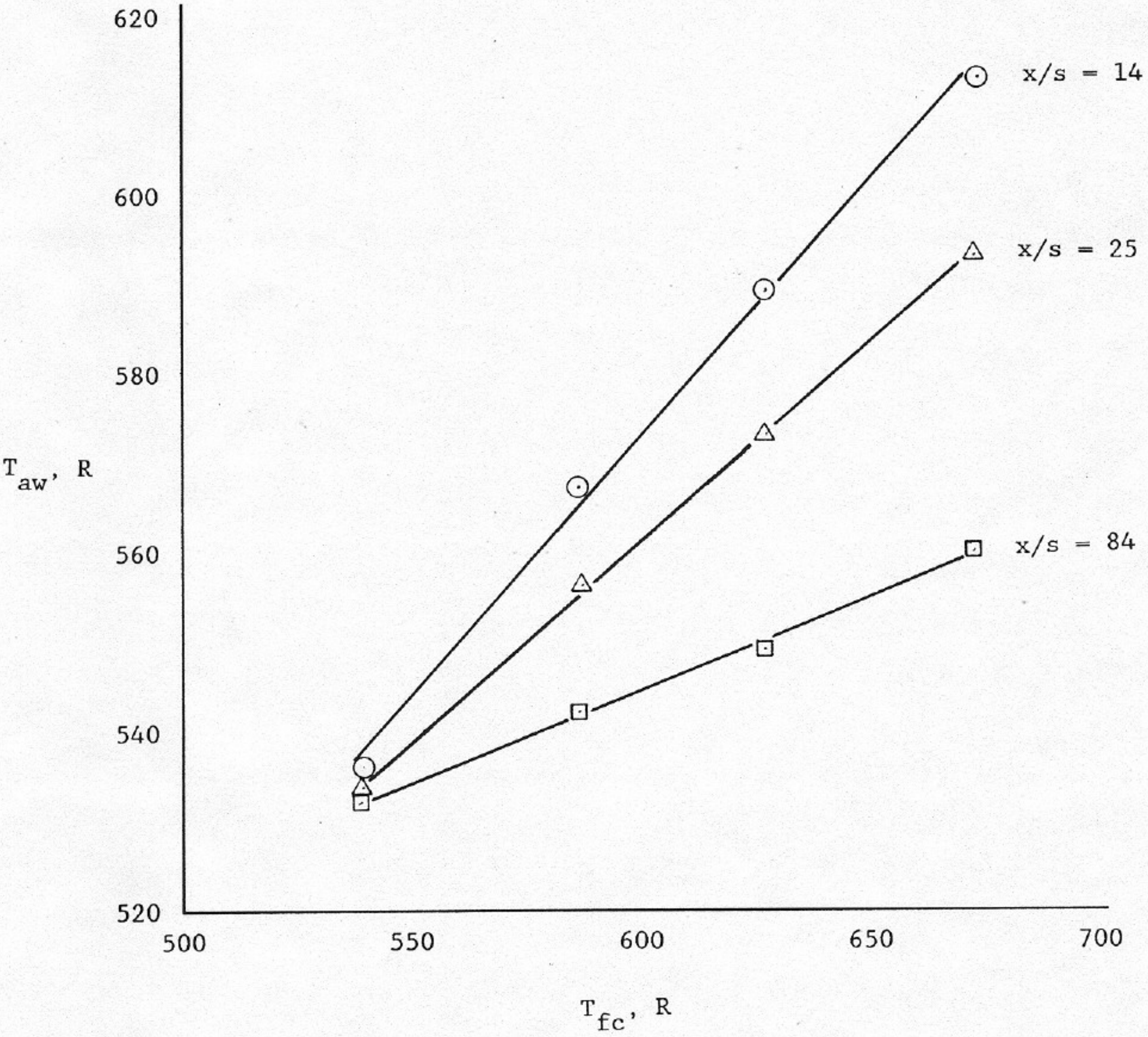

FIGURE 1 FILM HEATING THERMAL BEHAVIOR--DATA FROM HARTNETT, BIRKEBAK, AND ECKERT (1961) FOR SLOT GEOMETRY, s = 0.123", M = .28, MACH NUMBER = 0.15, T_{ms} = 530 R.

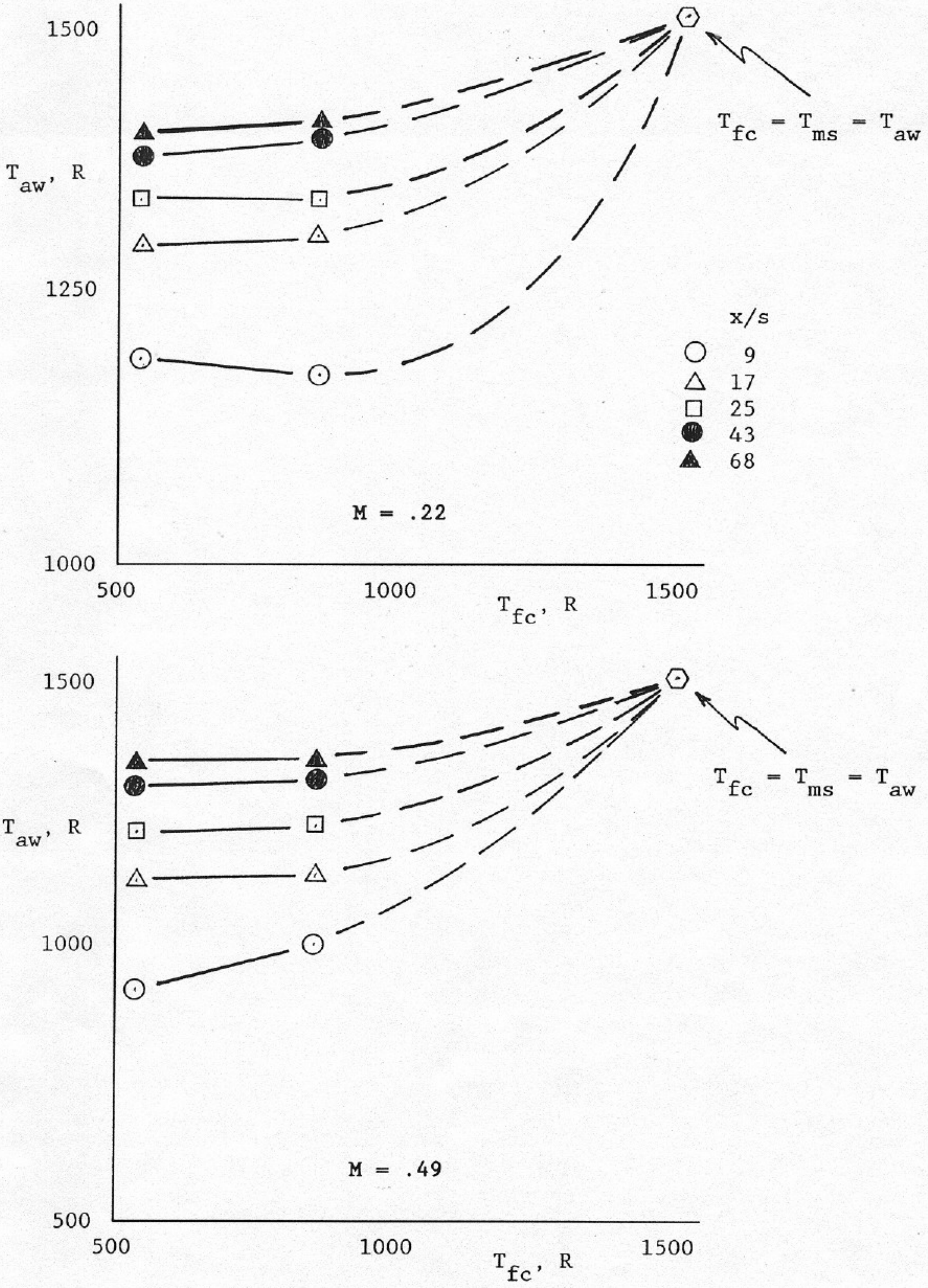

FIGURE 2 FILM COOLING THERMAL BEHAVIOR--DATA FROM PAPELL AND TROUT (1959)--SLOT GEOMETRY, s = .50", T_{ms} = 1510 R, MACH NO. = .22

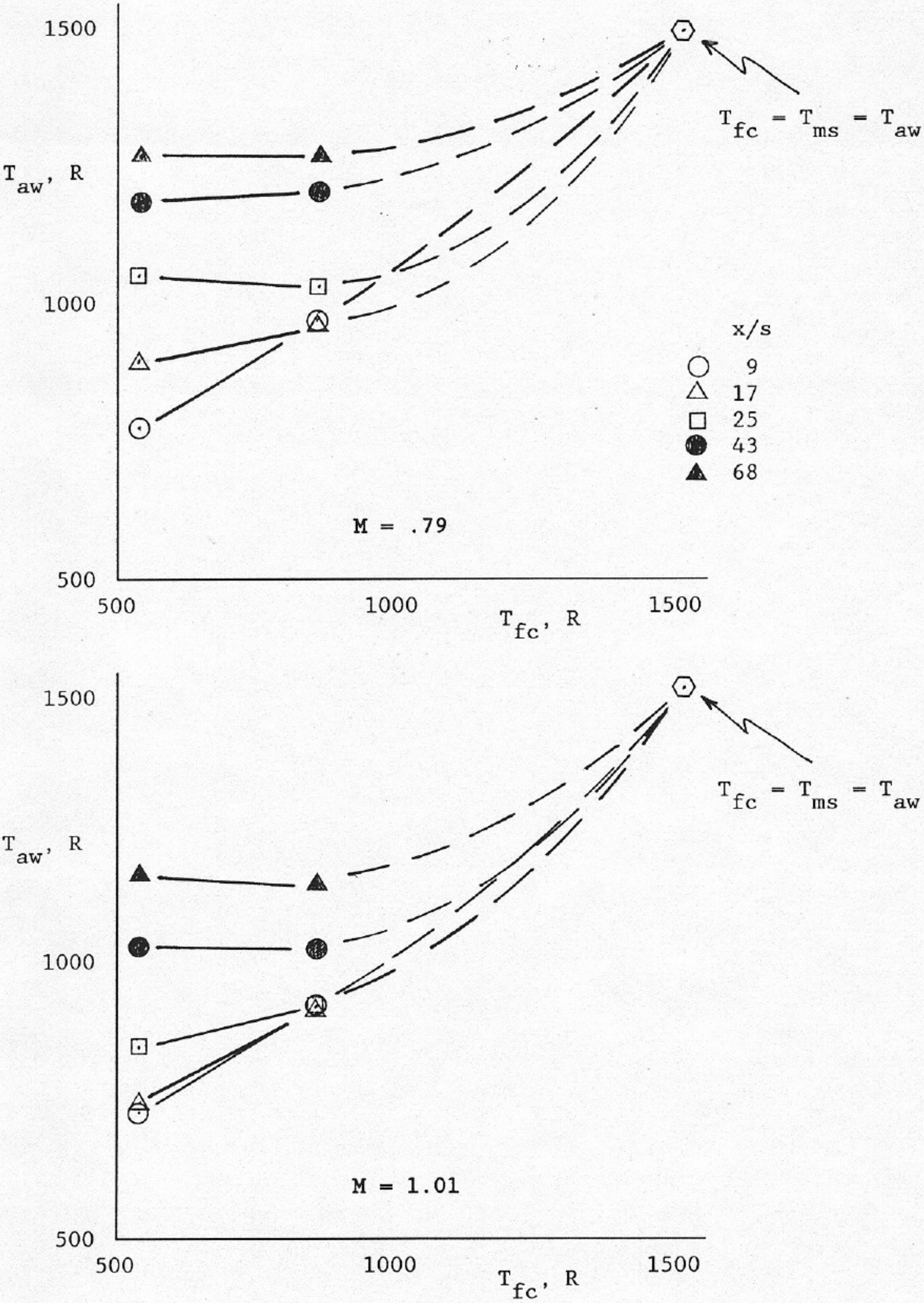

FIGURE 2 continued

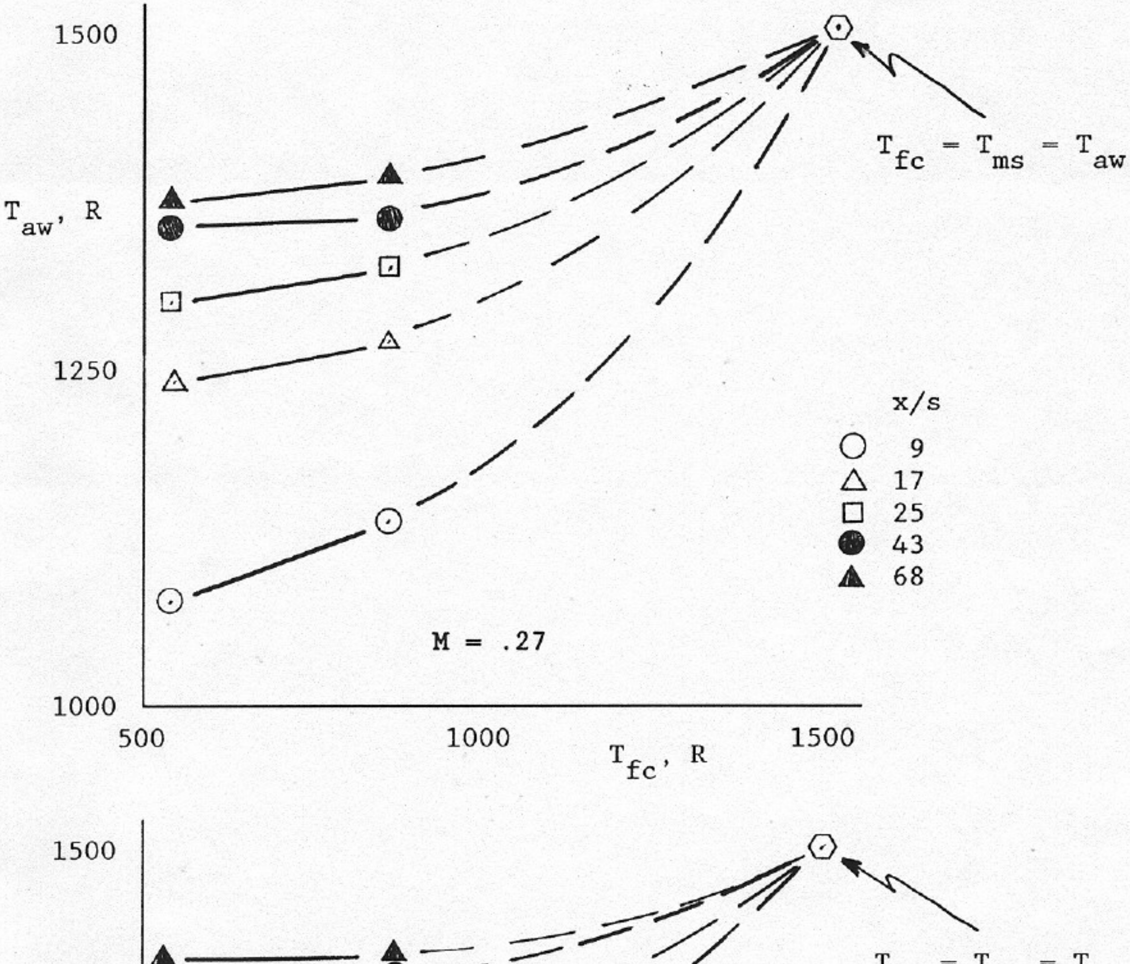

FIGURE 3 FILM COOLING THERMAL BEHAVIOR--DATA FROM PAPELL AND TROUT (1959)--SLOT GEOMETRY, s = .50", T_{ms} = 1500 R, MACH NO. = .50

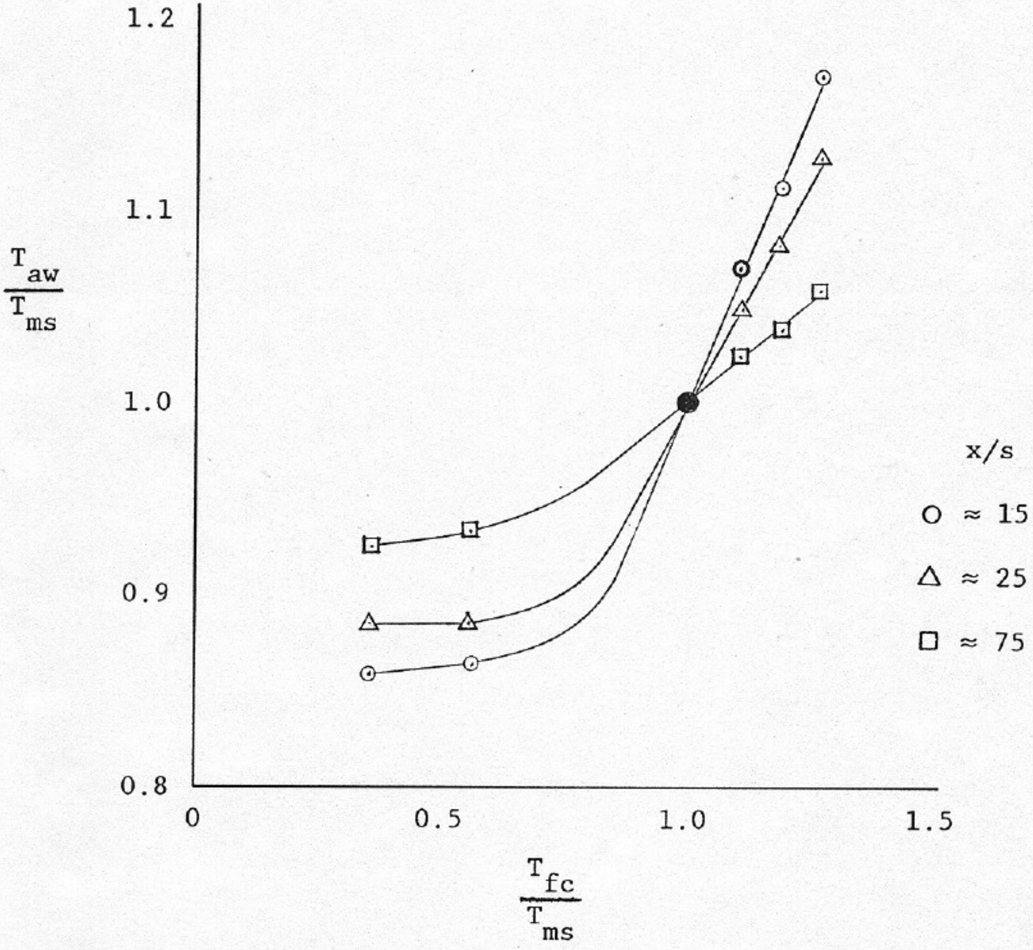

FIGURE 4 FILM COOLING/HEATING THERMAL BEHAVIOR IN DIMENSIONLESS FORM-- DATA BY PAPELL AND TROUT (1959), AND HARTNETT ET AL (1961)