Comparisons of Rational Engineering Correlations of Thermophoretically-Augmented Particle Mass Transfer with STAN5-Predictions for Developing Boundary Layers

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COMPARISONS OF RATIONAL ENGINEERING CORRELATIONS OF
THERMOPHORETICALLY-AUGMENTED PARTICLE MASS TRANSFER
WITH STAN5-PREDICTIONS FOR DEVELOPING BOUNDARY LAYERS

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SUMMARY

Fouling (and corrosion) of gas turbine (GT) blading often results from
the deposition of materials derived from inorganic impurities in the fuel
and/or ingested air. When the depositing material is in the form of a sub-
micron "aerosol" (dust or mist) it has been found that the rates of deposition
on cooled surfaces can be augmented by some 100-1000-fold via the mechanism of
thermophoresis (particle migration down a temperature gradient). For this
reason, in earlier papers we reported the development of rational, yet simple,
engineering correlations of thermophoretically-augmented particle transport
across both laminar boundary layers (LBLs) and turbulent boundary layers
(TBLs). While developed based on theoretical considerations, and numerical
computations of self-similar LBLs and law-of-the-wall (Couette flow-like)
TBLs, these mass transfer coefficient (St m -) correlations, when applied
locally, may also prove useful in making engineering mass transfer predictions
for more complex geometries, including GT-blades. Pending additional con-
trolled experiments, insight into the local applicability of these cor-
relations can be gained by selected comparisons with numerical predictions for
developing BLs. This paper reports on our (a) modification of the code STAN5
to properly include thermophoretic mass transport, and (b) examination of
selected test cases of developing BLs which include variable properties,
viscous dissipation, transition to turbulence and transpiration cooling.
Under conditions representative of current and projected GT operation, local
application of our St m/St m 0- correlations evidently provides accurate
and economical engineering design predictions, especially for suspended
particles characterized by Schmidt numbers outside of the heavy vapor range
(say, Sc>10).

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INTRODUCTION

Accurate predictions of mass transport rates in nonisothermal forced convection systems are now essential to the gas turbine (GT) industry, among other technologies. Recently, a dramatic enhancement in small particle diffusional transport rates due to thermophoresis (particle drift down a temperature gradient) has been predicted for both internally cooled and transpiration-cooled surfaces across both self-similar laminar boundary layers (LBLs) (refs. 1 and 2) and law-of-the-wall turbulent (ref. 3) boundary layers (TBLs), including viscous dissipation (ref. 4). The magnitude and temperature dependence of this thermophoretic augmentation has been experimentally confirmed for LBL flow of combustion products containing submicron MgO-particles (ref. 5).

To facilitate engineering predictions, simple rational correlations have recently been developed (refs. 6 and 7). Until now their accuracy and applicability limits have been demonstrated using "exact" numerical calculations for self-similar BLs (refs. 1 and 4). One of our purposes here is to examine their behavior and accuracy in more complex BL-flows, under conditions representative of current and future GT-technology.

The availability of high-speed, large capacity computers has made it possible to examine the reliability of self-similar heat transfer correlations when applied locally to developing BL situations. Indeed, computer codes for both multidimensional laminar and turbulent flows have been developed by exploiting finite-difference techniques (refs. 8 and 9). Recently, with increased interest in GT blade fouling and/or corrosion problems, greater attention is being focused on small particle mass transfer across two-dimensional BLs (ref. 10). To make such predictions we have adapted the two-dimensional BL code STAN5 (ref. 11), which has previously been widely used for gas-side convective heat transfer predictions. This necessitated modifying the program to now include thermal (Soret) diffusion ("thermophoresis" for small particles) in the suspended particle mass conservation (particle-phase "continuity") equation. Toward this end, STAN5 predictions over the suction surface of a typical stator blade are here compared with the predictions of our earlier correlations (refs. 6 and 7) when applied locally to such developing BL situations. Of course, experimental data, both for blade cascades and operational turbines, will be the ultimate arbiter of whether our correlations and/or numerical BL codes (e.g., STAN5) presently and properly include all of the phenomena which dictate mass transport rates in the challenging GT environment.

NOMENCLATURE

- $B_m$ real blowing parameter, eq. (5)
- $-B_T$ thermophoretic suction parameter, eq. (6)
- $c$ mass fraction of particles in the local gas mixture
- $D$ Brownian diffusion coefficient of particles
- $Da$ effective Damkohler number, eq. (7)
- $Le$ Lewis number (ratio of particle Brownian diffusivity to host gas heat diffusivity)
mass flux at station e or w
Mach number
pressure
radius (for axisymmetric BL flow)
nose radius of the turbine blade
source; eq. (3)
Schmidt number (ratio of host gas momentum diffusivity (kinematic viscosity) to particle Brownian (mass) diffusivity)
St. Stanton number for heat transfer
St. Stanton number for mass transfer, including thermophoresis
St. Stanton number for mass transfer without thermophoresis and/or transpiration cooling
absolute temperature
temperature at the outer edge of Brownian diffusion boundary layer
fluid velocity in x-direction (parallel to wall)
fluid velocity in y-direction (normal to wall)
distance along the surface (measured from the forward stagnation point)
distance normal to surface
thermal diffusion factor of the particle/host gas combination
dynamic viscosity of host gas
density of host gas
stream function coordinate, \( \rho ur = \frac{\partial \psi}{\partial y}, \rho vr = -\frac{\partial \psi}{\partial x} \)
nondimensional stream function coordinate, \( \frac{(\psi - \psi_w)}{\psi_e - \psi_w} \)
pertaining to the outer edge of the boundary layer
effective
pertaining to reservoir conditions (transpiration coolant)
pertaining to the surface (wall)
pertaining to gas mixture at upstream "infinity"
boundary layer (L, laminar; T, turbulent)
gas turbine
partial differential equation
right hand side
ADDITION OF THERMOPHORESIS TO STAN5 BL CODE

Here we focus only on the suspended particle mass conservation PDE, which must include the thermophoretic flux term. Upon time-averaging, the simultaneous fluctuation of the thermophoretic speed and particle concentration produces a new "correlation" term. But this latter term (which may be called "eddy thermophoresis") is neglected based on arguments given in references 12 and 13. In the same notation as reference 11, the time-averaged particle mass conservation equation for the BL can then be written:

\[ \rho u \frac{\partial c}{\partial x} + \rho v \frac{\partial c}{\partial y} = \frac{1}{r} \frac{\partial}{\partial y} \left( r \frac{\nu_{\text{eff}} \frac{\partial c}{\partial x}}{\nu_{\text{eff}} \frac{\partial c}{\partial y}} \right) + \frac{1}{r} \frac{\partial}{\partial y} \left( \frac{r \rho \alpha T D c}{T} \frac{\partial T}{\partial y} \right) \]  

(1)

where the second term on the RHS of equation (1) is the added thermophoretic flux. Upon introducing the nondimensional stream function as the transverse coordinate (cf. ref. 11) equation (1) becomes:

\[ \frac{\partial c}{\partial x} + \left[ r \dot{m}_w + \omega (r \dot{m}_e - r \dot{m}_w) \right] \frac{\partial c}{\partial \omega} = \frac{\partial}{\partial \omega} \left[ r^2 \rho u \nu_{\text{eff}} \frac{\partial c}{\partial \omega} \right] = \frac{\partial}{\partial \omega} \left[ \frac{r^2}{\rho} \frac{\partial \alpha T D c}{\partial \omega} \right] \]  

(2)

In the numerical solution of equation (2) the thermophoretic flux term on the RHS will be treated as a "source" term. Although the source itself is explicitly \( c \)-dependent, \( c \)-values obtained from the previous (upstream) integration step are used in its evaluation. This simple treatment of the thermophoretic flux term is compatible with numerical approximations already incorporated in STAN5. For flow near the wall, where STAN5 switches to simplified Couette-flow equations (with no streamwise variation of the dependent variable, and constant \( r \)), the thermophoretic flux term is included in the particle mass conservation equation, again as the "source" defined by:

\[ S \equiv \frac{\partial}{\partial y} \left( \frac{\rho \alpha T D c}{T} \frac{\partial T}{\partial y} \right) \]  

(3)

Based on the procedures outlined in reference 14, new subroutines have been added to STAN5 in order to calculate the suspended particle thermal diffusion factor, \( \alpha_T \), and the Brownian diffusion coefficient, \( D \) (as well as the Schmidt number, \( Sc \)), including their respective temperature dependencies.
The modification in particle deposition rate due to thermophoresis depends both on particle size (hence Schmidt number) and the ratio of mainstream-to-surface-temperature. Therefore, under typical turbine operating conditions, in order to see an appreciable thermophoretic effect one needs to consider particles heavier than ordinary vapor molecules. However, as is well known, when the particle size increases (enough to cause $Sc \gg 1$), the mass transfer (Brownian diffusion) BL is completely imbedded within the momentum (or heat) transfer BL, the thickness ratio being proportional to $Sc^{-1/3}$ (or $Le^{1/3}$). In fact, it can be readily shown (ref. 1) that in the presence of "strong" thermophoresis (i.e., $\alpha [ (T_e/T_w) - 1 ] \gg 1$) the Brownian diffusion BL is even much thinner than in the absence of thermophoresis, with the thickness ratio scaling becoming proportional to $Sc^{-1}$ (or $Le^{1/3}$). These observations imply that a finite-difference scheme with a much finer mesh size is required for an accurate solution of the small particle concentration profile and the associated mass transfer Stanton number. Moreover, to preserve accuracy for a two-dimensional integration process, a thinner BL requires a smaller step-size in the x-direction -- i.e., x-direction step-size is restricted by the smallest of the momentum, heat and mass transfer BL thicknesses. Consequently, a moderate increase in the particle size (via $Sc$) increases the computation time dramatically. In order to achieve a reasonable balance between (a) sufficient thermophoretic deposition rate enhancement (to test the accuracy of our correlations) and (b) required computation time, we have therefore adopted a Schmidt number of about 26 for most of our trials (except for one case with $Sc = 100$, see "Results and Discussion"). Accordingly, the dimensioning of STAN5 has been increased up to 1000 mesh points in the y-direction (from the originally programmed maximum of 60 mesh points).

RESULTS AND DISCUSSION

For all results presented here a mainstream velocity distribution obtained from reference 15 for a turbine stator blade is used as input to STAN5. Except for figure 6, the nose radius, $R_n$, of the blade used for the illustrative calculations was taken to be 0.152 cm. Integrations were carried out along the suction surface up to about 10 nose radii from the blade stagnation point. In these cases the predicted BL flow remained laminar. To examine the consequence of transition to turbulence (by $x/R_n \approx 5$), for figure 6 the blade was magnified to $R_n = 0.366$ cm and the stagnation pressure was increased from 4 atm. to 20 atm.

In all figures, results at the stagnation point ($x = 0$) are obtained from the self-similar solutions of reference 1 (because STAN5 is singular at $x = 0$). STAN5 calculations are started at $x = 10^{-1} R_n$. Downstream results are very sensitive to the initial starting profile specified (see also [4].

[4] For the fastest commercially available computer, CRAY-1, using 800 mesh points in the y-direction and taking the step-size along the x-direction to be $10^{-1}$ times the local momentum BL thickness, integration of LBL equations by STAN5 along the suction surface of a typical turbine blade to about 10 nose radii downstream from the stagnation point required a CPU time of about 8 minutes with thermophoresis and 4 minutes without thermophoresis.
ref. 16). To be on the safe side, only STAN5-values beyond one nose radius from the stagnation point were considered reliable (initial profile insensitive). Moreover, by moving one nose radius away from the stagnation point we avoid any anomalies that may result due to (a) lack of accuracy in the mainstream velocity near the stagnation point (ref. 15), and (b) an unrealistic curve-fit generated by the cubic splines that STAN5 employs (ref. 17). The automatic starting profile generating subroutine of STAN5 (ref. 16) was used for the initial velocity and temperature profiles, and the velocity profile was scaled (via \( \text{Sc}^{-1/3} \)) to obtain the initial concentration profile.

The correlation values shown in all figures (with negligible viscous dissipation) are calculated from (refs. 6 and 7):

\[
\frac{St_m}{St_{m,0}} \approx \frac{-(B_m + B_T)}{1 - \exp (B_m + B_T) \cdot \exp(-Da)}
\]

(4)

where:

\[
B_m = \frac{\langle \rho v \rangle_w}{\langle \rho u \rangle_e St_{m,0}}
\]

(5)

\[
B_T = -(\alpha_T Le)_w \cdot \frac{St_h}{St_{m,0}} \cdot \frac{T_e - T_w}{T_w}
\]

(6)

and:

\[
Da = (\alpha_T Le)_e \cdot \frac{T_e - T_m}{T_m}
\]

(7)

The Schmidt numbers reported in the figures correspond to particles (assumed spherical) made up of \( \text{Na}_2\text{SO}_4 \) "monomer units" in air\(^5\). The ratio \( \alpha_T Le \) (of the thermophoretic diffusivity of the particles to the heat diffusivity of air), required for our correlations (ref. 6) was estimated to be 0.4 and temperature-independent for all reported cases here. For simplicity in the correlation scheme, throughout this paper the ratio: \( St_h/St_{m,0} \), of the Stanton number for heat transfer to the Stanton number for mass transfer without thermophoresis, was approximated to be equal to the prevailing value of \( Le_w^{-2/3} \) for laminar BL flows. However, for transitional and fully turbulent flows, local \( St_h \) and \( St_{m,0} \) values (as calculated by STAN5) are used for the correlation calculations.

To "calibrate" STAN5, we first ran the case of a flat plate (constant mainstream velocity), with the results shown in figure 1. The abscissa is the distance along the flat plate made nondimensional by the stator nose radius \( R_n = 0.152 \text{ cm} \) to allow comparisons with the abovementioned turbine blade example. The ordinate is the ratio of mass transfer Stanton numbers

\(^5\text{Sc}_{0.6} = 26 \) corresponds to \( 10^2 \) and \( \text{Sc} = 100 \) corresponds to \( 8 \times 10^2 \) \( \text{Na}_2\text{SO}_4 \) monomer units in a cluster.
Under the prevailing conditions there is more than a two-fold enhancement in the deposition rate due to thermophoresis. For this "self-similar" case the result obtained from the exact numerical calculations of reference 1 is shown by the dash-dot line (x-independent). The correlation-predicted value is the dashed line. The only difference between the results of reference 1 and STAN5 should be that due to the somewhat different treatment of variable host gas (air) thermodynamic and particle transport properties for this "cold" wall ($T_w/T_\infty = 0.6$) self-similar case\(^6\). However, in interpreting subsequent comparisons, the reader should recall that STAN5 does not quite give a constant (x-independent) enhancement.

Figure 2 displays the results of calculations for the suction surface of a stator blade, using the same environmental conditions as in figure 1. For the prevailing conditions the Mach number is calculated to be about $Ma_e = 0.72$ at $x/R_n = 10$ (less for smaller $x/R_n$). To display the effect of the Mach number STAN5 was also run including viscous dissipation. As expected (ref. 4), at these Mach numbers viscous dissipation is seen to have a small effect on the thermophoretic enhancement of deposition rates. Comparison of our correlations with STAN5 both with and without viscous dissipation shows that the local difference is always less than 10 percent. The shape of the curves (i.e., the fact that the effect of thermophoresis decreases as $x/R_n$ increases) can be explained by the mainstream static temperature cooling. Although $T_w/T_\infty$ is fixed for our calculations, the difference between the mainstream static temperature, $T_e$ (which gets cooler as the flow accelerates under adiabatic conditions), and the wall temperature, $T_w$ (constant), gets smaller, which reduces the effect of thermophoresis. Of course, our correlations are also applied locally, with the relevant local temperature being $T_e$ rather than $T_\infty$.

Figure 3 is constructed for the same conditions as figure 2 except that the wall temperature is higher ($T_w/T_\infty = 0.8$), corresponding to a smaller enhancement in deposition rate due to thermophoresis. The agreement between the predictions of STAN5 and our correlations is excellent.

In figure 4 an increased particle size is considered ($Sc_\infty = 100$), keeping all remaining parameters the same as in figure 3. The corresponding effect of thermophoresis is now even greater than in the colder wall case ($T_w/T_\infty = 0.6$) with $Sc_\infty = 26$ (shown earlier in fig. 2). Yet, the agreement between our correlations and STAN5-predictions is even better, with local differences being less than 4 percent for all $x/R_n$-values. This may be related to our observation (ref. 6) that for self-similar cases these correlations improve as $T_w/T_\infty \to 1$, regardless of particle size ($Sc$).

To consider even larger departures from self-similarity a variable (x-dependent) wall temperature was considered, with the results shown in figure 5. $T_w$ is varied in such a way that the wall is hottest at the stagnation point ($T_w/T_\infty = 0.8$) and gets colder as $x/R_n$ increases, becoming $T_w/T_\infty = 0.5$ at $x/R_n = 10$. Not surprisingly, the thermophoretic effect increases as the wall gets cooler (although the

\(^6\)Reference 1 assumes that the host gas thermodynamic and particle transport properties have simple power-law temperature dependencies.
mainstream static temperature drops as the flow accelerates, the reduction in
the assumed wall temperature is greater, resulting in a steeper temperature
gradient across the BL). While departures between the correlation and
STAN5-predictions increase as the wall-to-mainstream-temperature ratio departs
from unity (ref. 16), remarkably enough, the effects due to "nonself-
similarity" act in such a way that the agreement between STAN5 and the
correlations improve as $T_w$ drops.

In figure 6 the nose radius of the stator blade and the pressure have
been increased to 0.366 cm and 20 atm, respectively. The corresponding BL
flow becomes transitional at about $x/R_n = 2.9$ and "fully" turbulent at
about $x/R_n = 5.0$. A lower wall temperature ($T_w/T_m = 0.5$) is considered
to provide a stringent test of the present correlations, based (ref. 6) on
self-similar integrations for $T_w/T_m \geq 0.5$. We observe that the
agreement between STAN5 and our correlations improves for turbulent BLs. In
this connection it should be recalled that our correlations describe the
results of law-of-the-wall Couette-flow TBL integrations with even better
accuracy than in otherwise corresponding LBL situations. When compared
locally with STAN5 results, even for $T_w/T_m = 0.5$, agreement is within
10 percent for the laminar portion, and within 4 percent for the fully
turbulent portion of the flow. The agreement is still better in the
transitional region. Note that the effect of thermophoresis on mass transfer
(over and above the already efficient transfer mechanism by turbulent eddies)
is smaller than in the corresponding laminar BL case.

Figure 7 displays the results of our calculations on the effect of
transpiration cooling and/or thermophoresis on the deposition rate of small
particles ($Sc_a = 26$). For this purpose STAN5 was run with the wall
boundary condition specified as a flux (instead of a level), where the
reservoir temperature of the coolant air was taken to be 600K ($T_0/T_m = 0.4$). The correlation curve without thermophoresis is representative of how
the blowing rate was varied along the blade surface. The blowing rate was set
higher near the stagnation point, was reduced along the suction surface, and
near the trailing edge ($7 \leq x/R_n \leq 10$) was chosen such that the real blowing
parameter, $B_m$ (defined by eq. (5)), was constant.

If attention is first focused on the STAN5 and correlation curves without
thermophoresis, observe that STAN5-predictions "lag" in responding to local
blowing rate variations when compared with the correlation (which is based on
an "instant" assumed adjustment to the local blowing rate). Specifically,
for $7 \leq x/R_n \leq 10$, although the correlation predicts a constant reduction
in the deposition rate, STAN5-values steadily increase, ultimately approaching
the correlation prediction, but remaining below them due to "recollection" of
the "history" of higher upstream blowing rates. For a two-dimensional
developing BL each $x$-integration station provides the starting profile for
the next station in the forward "marching" process. Therefore, the flow
cannot instantaneously adapt itself to the "new" (continuously varying)
boundary conditions. A better example is provided if the cross-over points of
the curves with and without thermophoresis are compared for the correlation
($x/R_n \approx 7.4$) and STAN5 ($x/R_n \approx 8.2$). Because of mainstream static temper-
ature cooling and the small blowing rates used in this example, the wall
temperature becomes hotter than the mainstream static temperature at about
$x/R_n \approx 7.4$. Although thermophoresis enhances small particles deposition
rates toward colder walls ("suction" effect, ref. 6), for hot walls the
deposition rate is reduced due to what we have called "thermophoretic blowing." The correlation curve with thermophoresis, of course, exhibits an immediate reaction to the hotter wall, and crosses the correlation curve without thermophoresis at $x/R = 7.4 (T_w/T_e = 1)$. However, STAN5—with thermophoresis responds to the change to a hotter wall further downstream at $x \approx 8.2$ and predicts lower deposition rates than STAN5—without thermophoresis from then on. We estimate the "lag" in the reaction of STAN5 to be about 9 to 10 local momentum BL thickness for the conditions investigated here. For a blowing rate distribution with more abrupt changes we can therefore expect even larger local disparities between STAN5-predictions and such correlations. However, in such cases (with sharp boundary condition variations) it should be recalled that the reliability of STAN5 results themselves becomes questionable. Considering the cost and accuracy features of both methods, the comparisons shown in figure 7 suggest that local applications of our correlations will be satisfactory for most engineering design predictions on transpiration-cooled objects.

CONCLUDING REMARKS

To examine the behavior and accuracy of our recently proposed $St_m/St_m, \phi$-correlations of particle mass transport (ref. 6) when applied locally to developing GT-boundary layer situations, we have embarked on a program of selected numerical computations and controlled laboratory experiments (ref. 5). Progress in the former category is reported here, and in view of the widespread familiarity and use of the two-dimensional BL code STAN5 (ref. 11 and 9) for GT heat transfer predictions, we have described how STAN5 has been adapted for mass transfer (deposition) rate predictions for cooled combustion turbine blades. Most importantly, the program has been modified to include thermal (Soret) diffusion ("thermophoresis" for small particles) in the suspended particle mass conservation equation. The transport properties (i.e., Brownian diffusion coefficient, thermal diffusion factor) of small particles (considered simply as "heavy molecules") are calculated allowing for their variation with temperature across the boundary layer. The program dimensioning is increased to accurately obtain the suspended particle concentration profile inside the much "thinner" (cf., thermal and momentum boundary layer thickness) mass transfer (Brownian diffusion) boundary layer for small particles ($Sc \gg 1$).

STAN5 predictions of mass transfer coefficients are then used to examine the behavior and accuracy of correlations we recently developed to predict the enhancement in deposition rates due to thermophoresis in the presence of variable properties, transpiration cooling and/or viscous dissipation. These correlations, which successfully described results for self-similar laminar boundary layers, and law-of-the-wall turbulent boundary layers (ref. 6), are here found to be quite satisfactory and very economical, when applied locally to developing laminar and turbulent high Schmidt number mass transfer boundary layers.

Whatever is projected for electronic computational capabilities, more realistic system predictions/optimizations will inevitably require subroutines.

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7 See reference 18 for a comparison of STAN5 predictions with experimental heat transfer around a gas film-cooled cylinder in cross-flow.
which economically incorporate the results of prior BL integrations. In view of the complexity and the often prohibitive cost of running repetitive PDE simulations for day-to-day engineering design calculations, the comparisons discussed here suggest that local application of our previous mass transfer correlations (ref. 6) can cover typical cases of GT-interest with acceptable accuracy.

REFERENCES


FIG. 1 Accuracy of STAN 5 \([11]\) and correlations \([6, 7]\) in predicting the thermophoretic enhancement of particulate mass transfer rates when compared to self-similar laminar boundary layer calculations \([11]\) for a flat plate; \(\text{Sc}_\infty = 26, \frac{T_W}{T_\infty} = 0.6\).

FIG. 2 Comparison of correlations \([6, 7]\) with STAN 5 \([11]\) predictions of mass transfer rate enhancement due to thermophoresis both with and without viscous dissipation; GT stator \([15]\), \(\text{Sc}_\infty = 26, \frac{T_W}{T_\infty} = 0.6\).
FIG. 3 Comparison of correlations [6, 7] with STAN 5 [11] predictions of mass transfer rate enhancement due to thermophoresis; GT stator [15], $Sc_{\infty} = 26$, $T_w/T_\infty = 0.8$.

$\frac{St_m}{St_{m,0}}$

$X/R_n$

FIG. 4 Comparison of correlations [6, 7] with STAN 5 [11] predictions of mass transfer rate enhancement due to thermophoresis; GT stator [15], $Sc_{\infty} = 100$, $T_w/T_\infty = 0.8$. 

$\frac{St_m}{St_{m,0}}$

$X/R_n$
FIG. 5 Comparison of correlations [6, 7] with STAN 5 [11] predictions of mass transfer rate enhancement due to thermophoresis for a variable wall temperature, GT stator [15] ($T_w/T_\infty = 0.8-0.5$).

FIG. 6 Comparison of correlations [6, 7] with STAN 5 [11] predictions of mass transfer rate enhancement due to thermophoresis allowing transition to turbulence; GT stator [15], $Sc_{\infty} = 26$, $T_w/T_\infty = 0.5$. 
FIG. 7 Comparison of correlations [6, 7] with STAN 5 [11] predictions of mass transfer rate reductions in the presence of gas transpiration cooling, both with and without thermophoresis; GT stator [15].

$Sc_m = 26, \frac{T_0}{T_\infty} = 0.4, T_\infty = 1500 \text{ K}, p = 4 \text{ atm}$
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