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Application of a surface renewal model to the prediction of heat transfer in an impinging jet

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Abstract—The concept of surface renewal is applied to an impinging heated planar jet to predict the local heat transfer coefficient distribution near impingement. The modeling concept is based on a zonal approach which identifies an outer flow and an impingement region. The outer region flow is determined by using the standard k–ε model. The impingement region is modeled using the surface renewal concept. In the application of the surface renewal model the solution is sensitive to the zonal matching and initial conditions imposed. Results show very good agreement with experimental data when the jet centerline conditions are used to scale the initial velocity and temperature renewal process. The renewal frequency for momentum is derived from experimental data. The thermal energy renewal is modeled based on a renewal frequency developed from the consideration of a displaced temperature spectrum which is consistent with experimental results. Overall, the use of the surface renewal model in the impingement region is shown to be an attractive alternative approach in the prediction of the surface interactions.

INTRODUCTION

IN THE treatment of turbulent flows near a surface, the application of the standard k–ε model, which is normally used for regions of very high Reynolds number, is not satisfactory. Usually a wall function or a low Reynolds number modification is used in the near wall regions. The application of such models is often based on the assumption of local equilibrium between turbulent production and dissipation. In the near impingement region of an impinging jet, the existence of strong streamline curvature, resulting in a stabilizing condition, and the presence of large velocity gradients tends to reduce the shear stress in this region and cause anisotropy, Pelfrey and Liburdy [1, 2]. Therefore, a different approach for treating the effects of the near wall turbulence is generally needed to study the flow and thermal fields.

Childs and Nixon [3] indicate a need for a higher order turbulence model to better predict the influence of curvature as well as the near impingement anisotropic turbulence. The disagreement between the predicted and the experimental heat transfer coefficients using a k–ε model, as documented by Looney and Walsh [4], can be attributed to the complex structure in the near impingement region. This warrants a turbulence model which is more consistent with some of the important physics of the flow field that have been found in experimental studies.

Recently there has been significant insight into some aspects of the surface renewal mechanism in complex flow geometries using flow visualization techniques. The physical behavior in the near wall region of boundary layer type flows has been characterized by previous investigators by the direct interaction between large eddies and the surface. To a great degree the near region impingement of jets consists of large scale structure interactions with the surface. Kestin and Maeder [5] postulated the existence of an amplification of vorticity fluctuations which is responsible for the observed enhancement of heat transfer in the neighborhood of the stagnation point. The enhanced heat transfer in the impingement region was experimentally studied by Kataoka and Mizushita [6]. They found, for a Prandtl number of 10^3, that the local enhancement of Nusselt numbers was attributed to the penetration of nonuniform turbulence of the free-stream across the laminar boundary layer and the subsequent transition from a laminar to a turbulent boundary layer. For their experimental conditions the local heat transfer coefficient was a maximum when the surface was located six nozzle diameters from the jet exit. Yokobori *et al.* [7], following the vorticity amplification premise of Kestin and Maeder [5], investigated the production mechanism of large scale eddies using flow visualization. They found that large scale longitudinal vortex-like structures are formed in the near region of the jet and contribute to the surface interaction. They concluded that these structures are predominant in the passive transport in the impingement region. In several other experimental studies the maximum heat transfer coefficient has been found to occur at a jet nozzle spacing, nondimensionalized as H/d, between seven and eight, where H is the plate

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NOMENCLATURE

C_f	surface friction factor
d	width of the jet nozzle
f	frequency
H	distance from the jet exit to the surface
k	thermal conductivity; turbulence kinetic energy
Nu	Nusselt number, hd/k
p	pressure
P	nondimensional pressure, $(p-p_\infty)/\rho v^2$
Pr	Prandtl number, ν/α
Re	Reynolds number, $v_j d/\nu$
s	dominant frequency for renewal
S	nondimensional frequency used in the surface renewal model, sd/v_j
S_t	nondimensional frequency used for thermal transport, $s_t d/v_j$
St_n	Strouhal number, defined in equation (12)
S_Ψ	source term
t	temperature
T_j	nozzle exit temperature
T_s	surface temperature
u	velocity component, x direction
U	nondimensional mean velocity, x direction, u/v_j
v	velocity component, y direction
v_j	nozzle exit velocity
V	nondimensional mean velocity, y direction, v/v_j
x	coordinate along the impinging surface from the stagnation point
X	nondimensional x, x/d
y	coordinate normal to the surface
Y	nondimensional y, y/d.

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
Γ	diffusion coefficient
ε	turbulence kinetic energy dissipation rate
θ	nondimensional temperature, $(t-T_s)/(T_j-T_s)$
λ	time variable during the surface renewal process
ν	kinematic viscosity
ρ	density
ϕ	statistical age distribution
ψ	generalized variable.

Subscripts

i	index representing vector component
l	inrush condition
k	turbulence kinetic energy
s	surface value
t	thermal
ε	turbulence kinetic energy dissipation rate.

distance from the nozzle exit and d is the size of the nozzle opening. Most explanations of this have been based on two dimensional flow considerations of a maximum interaction between the centerline turbulence intensity, which increases with increasing H, and the mean arrival velocity, which decreases with H. Aside from this explanation, Yokobori *et al.* [7] reasoned this result from the scaling of the three dimensional eddy structure based on nozzle size and exit velocity. The dominant frequency associated with the large eddies at the end of the potential core was found by Browand and Laufer [8] to be independent of the Reynolds number.

Gutmark *et al.* [9] studied the characteristics of far field impinging turbulent jets, $H/d = 100$, and Menon and Liburdy [10] studied jet impingement in the near field and for a fully developed jet, $H/d = 8$ and 32. Both studies found that the effects of the wall occurred at approximately $0.2H$ from the surface. They also found a neutral frequency which distinguishes those eddies being amplified from those being dissipated by viscous effects near the surface. A similar result was observed by Pelfrey and Liburdy [1] in the impingement region of an offset jet. The neutral frequency was found to scale with nozzle size, impinging plate separation distance and exit velocity. This evidence indicates that large scale structures dominate the impingement region and must be accounted for in an appropriate turbulence model.

The concept of a surface renewal model was initially developed for flow over flat plates. The notion proposed by Danckwerts [11] is that eddies intermittently move from the turbulent core into the wall region while exchanging momentum and energy during their lifetime. In a theoretical study of the rate of gas absorption in a liquid flow by Higbie [12] it was concluded that the conventional concept of a viscous sublayer as a stagnant film was not valid in many situations when the contact time of absorption is less than the penetration time. Rather, the turbulence penetrates into the surface continually and is replaced with high speed renewed fluid during the absorption period. Einstein and Li [13] also observed the unsteady nature of the viscous sublayer and proposed a mathematical model based on a cyclic growth and decay phenomenon. They concluded that with the quasi-steady sublayer concept it is impossible to explain the periodic creation of turbulence in this region. The scale of the sublayer thickness was estimated, in accordance with experimental data, to be on the order of the local wall unit. The inrush velocity was chosen iteratively so that the predicted velocity profile matched experimentally measured values. However, their assumption of a constant velocity in the turbulent flow adjacent to the sublayer is artificial and, according to the authors, was introduced only for mathematical convenience.

In this paper the surface renewal concept is extended to the modeling of the velocity and temperature fields of an impinging jet. In so doing some characteristics of the renewal process are based on experimental results in the literature. Further detailed experimental verification is required to determine the validity of the proposed procedure, especially if extended to other flow geometries and boundary conditions. However, if such an approach proves to be a good modeling tool it has the advantage of being easy to use and computationally efficient.

MATHEMATICAL MODEL

The surface renewal model requires a description of multiple, large eddies simultaneously existing within the domain of interest. Each eddy is assumed to have a unique age at any given time. The life of each eddy within the impingement region is characterized by an inflow followed by an outflow at some later time. In an impinging jet flow the large scale energy containing eddies are assumed to impinge with a characteristic frequency. The determination of this frequency is discussed later. Visual evidence of the large scale interaction for an impinging jet flow is provided by Kataoka *et al.* [14].

The instantaneous equations governing the transport of mass, momentum and heat associated with the life of the large eddies within the impingement region are used to describe the renewal process. The turbulence mechanism responsible for enhanced momentum and thermal energy transport is modeled in terms of primarily large scale coherent structures. The structures are characterized by frequency of occurrence, a specified boundary condition upon entering the impingement region, and an initial condition of the structure distribution within the impingement region. Formulation of the model begins with the conservation equations of mass, momentum and energy written as

$$\partial u_i/\partial x_i = 0 \tag{1}$$

$$\partial u_i/\partial \lambda + u_j\, \partial u_i/\partial x_j = -\partial p/\rho\, \partial x_i + \nu\, \partial^2 u_i/\partial x_j^2 \tag{2}$$

$$\partial t/\partial \lambda + u_j\, \partial t/\partial x_j = \alpha\, \partial^2 t/\partial x_j^2 \tag{3}$$

where λ represents the time during the life of an eddy, or age, and the model is limited to nonbuoyant incompressible, constant property flow.

The variables are transformed using a statistical age distribution. The ensemble average of a generalized variable ψ, which represents a velocity component or temperature, is related to its instantaneous distribution by assuming a probability function, ϕ. The probability function is prescribed as an age distribution based on a characteristic occurrence frequency, s, and information regarding the boundary and initial conditions. A possible functional form for the age dependence is $\phi = s \exp(-\lambda s)$ suggested by Danckwerts [11] and used by Thomas [15] for boundary layer flow. Assuming the ergodic conditions that time and ensemble averages are identical for a stationary process, Ψ represents the time average distribution. It is shown by Danckwerts [11] that the results are more sensitive to the choice of the frequency parameter, s, rather than the functional form of ϕ. So, rather than attempt to specify a unique age distribution the above relationship will be used.

The Navier–Stokes equations are reformulated by using the temporal distribution function, ϕ, and then integrating over the time domain resulting in

$$\partial \overline{u_i}/\partial x_i = 0 \tag{4}$$

$$s(\overline{u_i} - u_{1i}) + \overline{u_j\, \partial u_i/\partial x_j} = -\partial \bar{p}/\rho\, \partial x_i + \nu\, \partial^2 \overline{u_i}/\partial x_j^2 \tag{5}$$

$$s_t(\bar{t} - t_1) + \overline{u_j\, \partial t/\partial x_j} = \alpha\, \partial^2 \bar{t}/\partial x_j^2 \tag{6}$$

where u_{1i} and t_1 represent the velocity and temperature fields at the instant of the inflow process, respectively, and the barred terms represent the ensemble average.

In the above model equations the inflow term, $s(\overline{u_i} - u_{1i})$, represents the contribution from the eddy transport mechanism. Similarly, the term $s_t(\bar{t} - t_1)$ is the thermal transport and is assumed to have a similar age distribution as the velocity, but possibly a different frequency, s_t. The terms $\overline{u_j\, \partial u_i/\partial x_j}$ and $\overline{u_j\, \partial t/\partial x_j}$ represent effects of the unsteady convective interaction between eddies which contribute to the total transport mechanism. The convective terms have been simplified in this application based on the assumption of relatively minor contributions from eddy–eddy interactions. These terms can be written as (using the momentum equation for illustration)

$$\overline{u_j \frac{\partial u_i}{\partial x_j}} = \bar{u}_j \frac{\partial \overline{u_i}}{\partial x_j} + \overline{\phi_{ij}}. \tag{7}$$

The first term on the right hand side represents the mean flow convective contribution to the transport process. The second term represents a higher order term whose value depends on large structure interaction of momentum (or velocity–temperature correlation in the energy equation). These higher order terms are taken to have relatively little contribution compared to the large structure inflow terms. This condition is expected to be valid in the presence of large coherent structures. Therefore, we are left with a single term which represents the turbulence effects (not unlike the Reynolds stress formulation that relies on modeling the correlation terms).

To complete the formulation of the problem for the surface renewal model, initial and boundary conditions are required. Equations (4), (5) and (6) are applied near the impingement region and are forced to match the k–ε model in the jet development region. The initial condition for renewal is to be some representation of the flow and temperature fields at the instant of the inflow process which transfers momentum and heat with velocity u_{1i} and temperature t_1 at $\lambda = 0$. Earlier studies using the surface renewal model for turbulent boundary layer flows suggested that the initial condition, u_{1i}, be the free-stream velocity. This was used successfully in the prediction of the skin friction coefficient by Thomas [15]. From a physical viewpoint it is not necessarily a justified assumption. In the impinging jet flow, at the instant of inflow, it is assumed that the incoming flow is not influenced by the presence of the wall. In the next instant the effects of the surface become evident and the ejection of fluid from the wall region follows. Based on this, the initial conditions for the impingement region are set equal to the mean jet conditions at a distance sufficiently far from the surface. Since experimental results indicate that both the mean and fluctuating quantities are essentially uneffected by the surface at a distance of $0.2H$ from the surface, this was taken as the location to evaluate the initial conditions for renewal. The initial conditions are to be specified by the k–ε solution of the flow outside of the impingement region. In this sense the surface renewal application becomes a zonal model linked to the k–ε model predictions of the flowfield from the nozzle exit up to the impingement region.

Boundary conditions are required at the wall, the centerline, at the outflow as the wall jet develops, and at the interface between the two modeling regions. At the wall and at the centerline no slip conditions and symmetry are imposed, respectively. At the interface boundary the mean velocity and temperature are matched to the solution from a k–ε model. The wall-jet development boundary conditions are based on near fully developed flow for the mean velocity and temperature such that the downstream derivatives are set to zero. Based on numerical experiments, this latter condition was found to have very little or no effect on the solution provided the boundary was sufficiently far downstream of impingement, Yuan [16].

With the above conditions and assumptions the two dimensional governing equations are given below in nondimensional form. The scaling parameters are v_j, the velocity at the jet exit, d, the width of the jet exit and $(T_j - T_s)$, the temperature difference between the jet exit and the surface

$$\partial U/\partial X + \partial V/\partial Y = 0 \quad (8)$$

$$S(U-U_1) + U\,\partial U/\partial X + V\,\partial U/\partial Y = -\partial P/\partial X + 1/Re\,(\partial^2 U/\partial X^2 + \partial^2 U/\partial Y^2) \quad (9)$$

$$S(V-V_1) + U\,\partial V/\partial X + V\,\partial V/\partial Y = -\partial P/\partial Y + 1/Re\,(\partial^2 V/\partial X^2 + \partial^2 V/\partial Y^2) \quad (10)$$

$$S_t(\theta-\theta_1) + U\,\partial\theta/\partial X + V\,\partial\theta/\partial Y = 1/Re\,Pr\,(\partial^2\theta/\partial X^2 + \partial^2\theta/\partial Y^2) \quad (11)$$

where θ is the nondimensional temperature and is defined along with Re, Pr, S and S_t in the Nomenclature. S and S_t take the form of a Strouhal number based on the nozzle width and jet exit velocity.

The selection of the computation domain for the application of the surface renewal model should be determined by the extent of influence of the surface on the flow characteristics. From the data of Gutmark *et al.* [9], for $H/d = 100$ and Menon [17], for $H/d = 8$ and 32, the mean flow and turbulent intensity is affected by the surface within a region $0.2H/d$ from the wall. So even for a wide range of H/d the impingement region can be taken as $0.2H/d$ from the surface. The lateral extent of the model (along the surface) was $x/d = 11.5$. Extending beyond this value does not change the solutions presented here.

The frequency, s, may be specified based on inferences from existing experimental data. However, it must be cautioned that there is no definitive evidence as to the universal nature of the results at this time. The neutral frequency mentioned previously was identified by Gutmark *et al.* [9] using the power spectra of the components of the fluctuating velocity along the jet centerline. They nondimensionalized this frequency using local velocity and length scales based on the corresponding values of the centerline velocity and jet width that would exist at the position of the surface if the surface was not present. Scaling the local velocity and width with the nozzle exit conditions results in a Strouhal number

$$St_n = fH/v_j(H/d)^{1/2} \quad (12)$$

which is related to the nondimensional frequency S as

$$S = St_n(H/d)^{-3/2}. \quad (13)$$

The measured value of the Strouhal number associated with the neutral frequency was found by Gutmark *et al.* [9] to be 5.6 for $H/d = 100$. The study of Menon [17] measured the neutral frequency Strouhal number to be near 6.2 for $H/d = 32$. It should be noted that experimental uncertainty is fairly high in determining this value.

In implementing the surface renewal model the problem was first solved using a k–ε model with a standard wall function near the surface. After a converged solution was achieved, the surface renewal model was applied to the impingement region of interest. Based on the surface renewal model results the local surface friction coefficient and heat transfer coefficient were calculated.

NUMERICAL PROCEDURE

The governing equations were solved using the control-volume approach of Patankar [18] applied to both the initial k–ε formulation and the surface renewal model, equations (8)–(11). All of the equations can be cast in the form:

$$\partial(\rho U_i \Psi)/\partial x_i = \partial(\Gamma\,\partial\Psi/\partial x_i)\partial x_i + S_\Psi \quad (14)$$

where Ψ is a generalized variable, Γ is a diffusion coefficient, and S_Ψ is a source term. The quantities Γ

Table 1. The transport equation for surface renewal model

Equation	Ψ	Γ	S_Ψ
x-Momentum	U	$1/Re$	$-\partial p/\partial x - Sd/U_j(U-U_1)$
y-Momentum	V	$1/Re$	$-\partial p/\partial y - Sd/U_j(V-V_1)$
Energy	θ	$1/(Re\ Pr)$	$-Sd/U_j(\theta-\theta_1)$

and S_Ψ are specific for a particular variable Ψ. For the surface renewal formulation the variables are listed in Table 1. Note that the turbulence modeling terms are contained in S_Ψ. The computational domain and boundaries are shown in Fig. 1. Since a staggered grid was used, boundary conditions were linearly interpolated as needed. The boundary I represents the interface between the free jet and impingement regions and is determined by the k–ε solution. The boundary conditions at II are based on symmetry and at IV on no slip and an isothermal surface. At boundary III, the velocity and temperature derivatives in the x direction are assumed to be negligible and were tested using successively larger grids until no significant change in the results was detected. A summary of the boundary conditions for the dimensionless velocity components and temperatures are given in Table 2. Grid dependency of the solutions was checked by varying the grid from 18×18 to 25×30 using a nonuniform grid. Less than a 1% difference of the surface friction and heat transfer was detected for this grid variation. The closest node to the surface was $0.005d$ which corresponded to a y^+ small enough to use the viscous flow formulation to evaluate the surface conditions (y^+ approximately equal to 0.4).

The choice of the initial conditions, or the so-called inflow contribution is not obvious. Two approaches are presented in this paper. One uses the interface boundary conditions determined by the k–ε model to specify the inflow initial values of, U_1, V_1, and θ_1. This results in a distribution of the inflow condition across the renewal region. The second approach bases the initial condition on the local velocity and temperature at the jet centerline at the interface of the impingement and the jet regions. This scaling assumes that the initial condition of momentum and thermal energy can be characterized by a single value at the jet centerline which appropriately represents the early stages of the renewal process.

Table 2. Boundary conditions (boundaries are indicated in Fig. 1)

Boundary I:	Upper boundary ($0.2H$ from the impingement surface) U, V, and θ are based on k–ε model solution of the jet
Boundary II:	Axis of symmetry $U = \partial V/\partial X = 0 = \partial\theta/\partial X = 0$
Boundary III:	Outflow boundary $\partial U/\partial X = \partial V/\partial X = \partial\theta/\partial X = 0$
Boundary IV:	Impingement surface $U = V = \theta = 0$

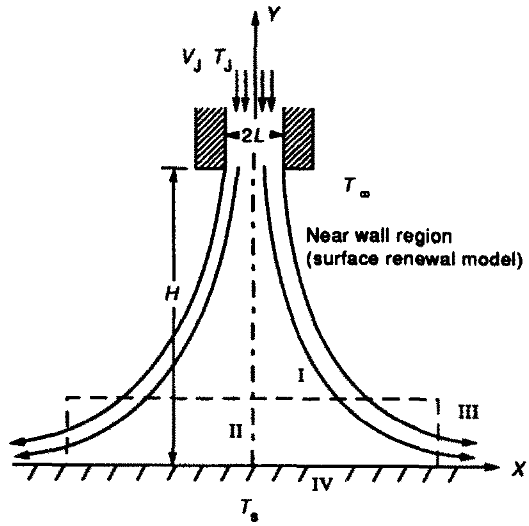

FIG. 1. Flow configuration, coordinate system, and impingement region boundaries.

RESULTS

The predictions of the surface interaction coefficients such as the skin friction and heat transfer rates using the surface renewal model are compared with experimental data in the literature. In each case considered the temperature difference was low enough to be nonbuoyant (low Richardson number). Additional results for buoyancy affected flows are presented by Yuan [16]. The skin friction coefficients have been measured by various researchers, the data of Beltaos and Rajaratnam [19] provide the necessary range of flow conditions for comparison with predicted values. The heat transfer coefficients are compared with the experimental data of Gardon and Akfirat [20] which provide a wide range of flow conditions.

Surface friction

Prior to solving the energy equation, used to predict the local heat transfer rate, the momentum equation was solved and used to evaluate the local surface friction coefficient, C_f. For this purpose the velocity derivative normal to the surface was estimated using a local finite difference approximation. Figures 2 and 3 show results of C_f for $H/d = 16$ and $Re = 7000$ and 11 000 respectively. Also included in the figures are the experimental results of Beltaos and Rajaratnam [19] where the shaded region represents results for the range of Reynolds numbers they investigated, from approximately 5600 to 9400. These predictions are based on an initial condition for renewal predicted by the k–ε model at the edge of the impingement region.

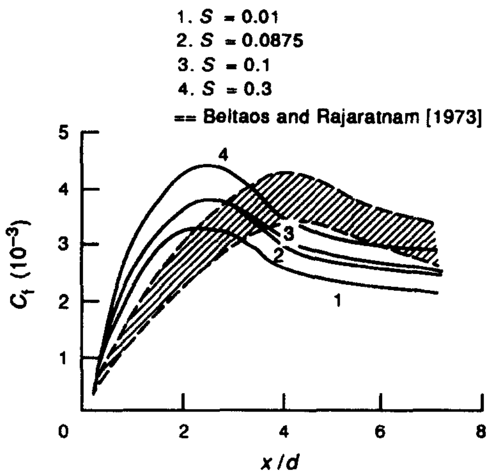

FIG. 2. Surface friction coefficient for a range of renewal frequency parameters using the distributed initial condition, $Re = 7000$, $H/d = 16$.

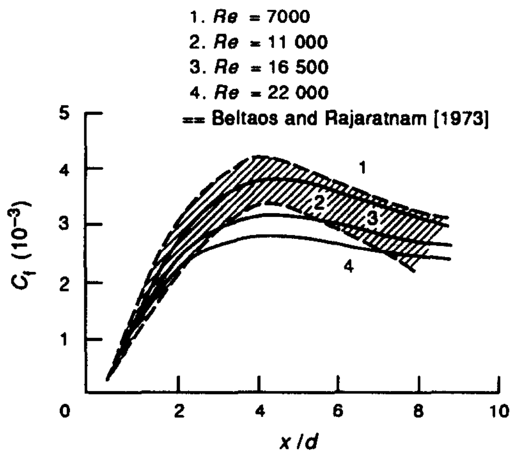

FIG. 4. Surface friction coefficient for $S = 0.0875$ using the centerline velocity for the initial condition, $Re = 11\,000$, $H/d = 16$.

The results are in poor agreement with the measured values, both in the distribution and location of the peak value. Efforts made to improve the results by varying S and adjusting the domain size and the grid did not improve the estimates.

The poor distribution of the C_f predictions led to the investigation of the appropriate initial condition for renewal. It is apparent that the scaling for the initial condition should not be based on the velocity distribution calculated from the k–ε model just outside of the impingement region. This scaling results in a skewed distribution which enhances the region near the jet centerline. The modeling of the large scale structures was modified by setting the initial condition for the entire impingement region equal to the centerline velocity predicted at the upper boundary of the impingement region. This provides a uniform initial condition consistent with a dominant structure which scales with the jet velocity prior to being influenced by impingement. Results of the local skin friction coefficients using this modified initial condition are presented in Fig. 4 for $H/d = 16$ and $S = 0.0875$ and a range of Reynolds numbers. This value of S is obtained using equation (12) with the neutral frequency Strouhal number $St_n = 5.6$ and $H/d = 16$. Results are in very good agreement with the experimental data of Beltaos and Rajaratnam [19]. Note that the specification of S, based on the Strouhal number, is independent of Reynolds number and is determined by H/d. Obviously, further understanding of the appropriate frequency and its relationship with the jet conditions is required. However, with limited available data, this modeling approach does very well.

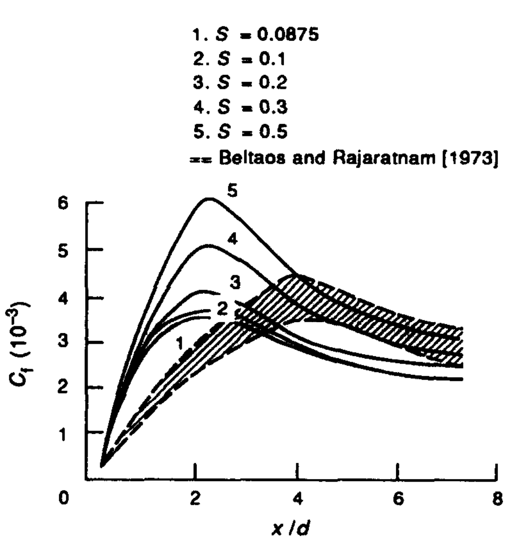

FIG. 3. Surface friction coefficient for a range of renewal frequency parameters using the distributed initial condition, $Re = 11\,000$, $H/d = 16$.

Heat transfer

A primary assumption in this model, as stated earlier, is that the surface renewal mechanism dominates the heat transfer process as well as the momentum transfer process. However, there is no evidence that both transport mechanisms occur at the same frequency. Allowing for a different representative frequency for heat transfer results in the parameter S_t in the energy equation. The velocity and temperature at the jet centerline predicted by the k–ε model at the upper boundary of the surface renewal region are used to define the initial condition of the thermal renewal process.

Some evidence of the characteristic frequency for heat transfer renewal can be obtained from Fulachier and Antonia [21] who studied the spectral analogy between velocity and temperature for a variety of flow conditions. They show how the one dimensional spectra shift depending on the velocity and temperature boundary conditions for flow over a flat sur-

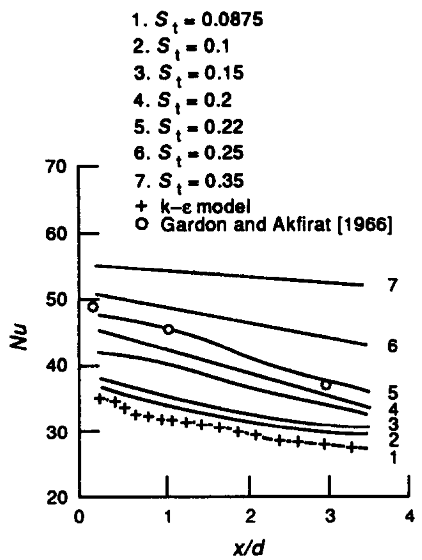

FIG. 5. Predicted local Nusselt number for a range of thermal energy renewal frequency parameters and $S = 0.0875$, $Re = 11\,000$, $H/d = 16$.

face. The most energetic portion of the fluctuating temperature spectrum is shifted to higher frequencies compared to the fluctuating velocity spectrum, particularly at distances away from the surface. The magnitude of the shift can be on the order of 2–5 times the dominate velocity frequency. For an impinging jet flow Menon [17] measured the velocity and temperature spectra along the jet centerline. He found that the temperature spectrum peak shifts to higher frequencies, compared to the velocity spectrum, just prior to impingement. This shift is of the order of 1.5–2 times the dominant velocity frequency for $Re = 8113$ and $H/d = 32$. This evidence suggests that the renewal frequency for heat transfer may occur at a higher frequency than for momentum transfer.

The prediction of the local surface heat transfer coefficient is presented in Fig. 5 for a range of S_t, all with $S = 0.0875$, for $Re = 11\,000$ and $H/d = 16$. Also shown are predictions using the k–ε model using the wall function suggested by Launder and Spalding [22]. The results indicate that the value of S_t must be significantly larger than S (2.5 times) in order to match the experimental results of Gardon and Akfirat [20]. The heat transfer coefficients near the stagnation point are slightly lower than the experimental data but the results, in general, are significantly superior to the prediction using the k–ε model. The surface renewal model was further tested with $S = 0.0875$ and $S_t = 0.22$ for different flow conditions. The results for $Re = 11\,000$ and $22\,000$ are compared to the experimental data of Gardon and Akfirat [20] in Fig. 6. The predictions are very good for both Reynolds numbers with the poorest agreement near the centerline where the prediction is about 10% lower than the experimental data for the high Reynolds number case. These results are not to suggest definitive values for S

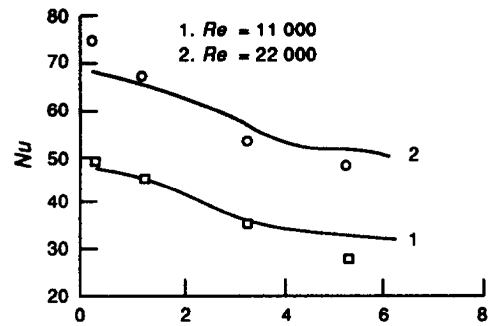

FIG. 6. Predicted local Nusselt number for two Reynolds numbers using $S = 0.0875$ and $S_t = 0.22$.

and S_t but indicate that further work is required that would allow for a better understanding of the relationship between Re and S_t and possibly other important parameters in the near field of the jet such as H/d and jet turbulence intensity.

CONCLUSIONS

We have demonstrated the use of a surface renewal model coupled with a k–ε model to predict the local heat transfer in an impinging jet. The method is easy to implement and provides good agreement with experimental data for the range of conditions studied. The general application of surface renewal for surface interactions requires further insight into the physical process. Experiments need to specify the spectral characteristics of momentum and heat transport. Particular attention needs to be paid to the distinction between the momentum and heat transport processes.

REFERENCES

1. J. R. R. Pelfrey and J. A. Liburdy, Effect of curvature on the turbulence of a two-dimensional jet, *Exp. Fluids* **4**, 143–149 (1986).
2. J. R. R. Pelfrey and J. A. Liburdy, Mean flow characteristics of a turbulent offset jet, *J. Fluids Engng* **108**, 82–88 (1986).
3. R. E. Childs and D. Nixon, Simulation of impinging turbulent jets, AIAA-85-0047, AIAA 23rd Aerospace Science Meeting, January (1985).
4. M. K. Looney and J. J. Walsh, Mean flow and turbulent characteristics of free and impinging jet flows, *J. Fluid Mech.* **147**, 397–429 (1984).
5. J. Kestin and P. F. Maeder, Influence of turbulence on transfer of heat from cylinders, NACA Tech. Note No. 4018 (1957).
6. K. Kataoka and T. Mizushita, Local enhancement of the rate of heat transfer in an impinging round jet by free turbulence, *Fifth International Heat Transfer Conference*, Tokyo, Paper FC-8-3, September (1984).
7. S. Yokobori, N. Kasagi, M. Hirate and N. Nishiwaki, Role of large scale eddy structure on enhancement of heat transfer in stagnation region of two dimensional, submerged, impinging jet, *Proceedings of Sixth International Heat Transfer Conference*, Vol. 5, pp. 305–310 (1978).
8. F. K. Browand and J. Laufer, The role of large scale structure in initial development of circular jet, *Proceedings of Fourth Biennial Symposium on Turbulence in Liquids*, Univ. of Missouri–Rolla, pp. 333–344 (1975).

9. E. Gutmark, M. Wolfshtein and J. Wygnanski, The plane turbulent impinging jet, *J. Fluid Mech.* **88**, 737–756 (1978).
10. R. Menon and J. Liburdy, Impingement characteristics of a heated two dimensional turbulent jet, ASME WAM, San Francisco (1989).
11. P. V. Danckwerts, Significance of liquid-film coefficients in gas absorption, *Ind. Engng Chem.* **43**, 1460–1467 (1951).
12. R. Higbie, The rate of absorption of a pure gas into a still liquid during short periods of exposure, *Trans. A.I.Ch.E.* **31**, 365–390 (1935).
13. H. A. Einstein and H. Li, The viscous sublayer along a smooth boundary, *Proc. ASCE J. Engr Mech. Div.* **82**, 1–27 (1954).
14. K. Kataoka, M. Suguro, H. Megawa, K. Maruo and I. Mihata, The effect of surface renewal due to large scale eddies on jet impingement heat transfer, *Int. J. Heat Mass Transfer* **5**, 305–310 (1987).
15. L. C. Thomas, A turbulent burst model on wall turbulence for two dimensional turbulent boundary layer flow, *Int. J. Heat Mass Transfer* **25**, 1127–1136 (1982).
16. T. D. Yuan, The study of buoyancy effects on laminar and turbulent plane impinging jets, Ph.D. Dissertation, Clemson University, Clemson, SC (1988).
17. R. Menon, Impingement characteristics of heat plane turbulent jets, Ph.D. Dissertation, Clemson University, Clemson, SC (1989).
18. S. V. Patankar, *Numerical Heat Transfer and Fluid Flow*. Hemisphere, Washington, DC (1980).
19. S. Beltaos and N. Rajaratnam, Plane turbulent impinging jet, *J. Hydraulic Res.* **11**, 29–59 (1973).
20. R. Gardon and J. C. Akfirat, Heat transfer characteristics of impinging two-dimensional air jets, *J. Heat Transfer* **88**, 101–108 (1966).
21. L. Fulachier and R. A. Antonia, Spectral analogy between temperature and velocity fluctuations in several turbulent flows, *Int. J. Heat Mass Transfer* **27**, 987–997 (1984).
22. B. E. Launder and D. B. Spalding, The numerical computation of turbulent flow, *Comp. Meth. Appl. Mech. Engr* **3**, 269–289 (1974).

APPLICATION DU MODELE DE RENOUVELLEMENT DE SURFACE A LA PREDICTION DU TRANSFERT THERMIQUE DANS UN JET IMPACTANT

Résumé—On applique le concept de renouvellement de surface à un jet chaud, planaire, impactant pour prédire la distribution du coefficient de convection près de l'impaction. La modélisation est basée sur l'approche zonale qui identifie un écoulement externe et une région d'impaction. La région externe est déterminée en utilisant le modèle classique k–ε. La région d'impaction est modélisée en utilisant le concept de renouvellement de surface ; dans cette démarche, la solution est sensible au zonage et aux conditions initiales choisis. Les résultats montrent un très bon accord avec les données expérimentales lorsque les conditions sur l'axe du jet sont utilisées pour caler la vitesse et la température initiale : La fréquence de renouvellement pour la quantité de mouvement est déduite des données expérimentales ; elle est développée à partir de la considération d'un spectre de température déplacée qui est cohérent avec l'expérience. Le modèle de renouvellement de surface dans la région d'impaction est une approche intéressante pour la prédiction des interactions à la surface.

ANWENDUNG EINES OBERFLÄCHEN-ERNEUERUNGSVERFAHRENS AUF DIE BERECHNUNG DES WÄRMEÜBERGANGS IN EINEM AUFTREFFENDEN STRAHL

Zusammenfassung—Das Konzept der Oberflächen-Erneuerung wird auf einen beheizten ebenen auftreffenden Strahl angewandt, um den lokalen Wärmeübergangskoeffizienten im Auftreffbereich zu berechnen. Hierbei wird ein Zonenverfahren benutzt, das zwischen einer äußeren Strömungszone und dem Auftreffbereich unterscheidet. Für die äußere Zone wird das k–ε-Modell verwendet. Der Auftreffbereich wird mit dem Oberflächen-Erneuerungsverfahren berechnet. Hierbei ist die Lösung von den Übergangsbedingungen zwischen den Zonen und der Anfangsbedingung abhängig. Die Berechnungen stimmen sehr gut mit Meßergebnissen überein, wenn Anfangsgeschwindigkeit und Temperatur-Erneuerungsvorgang mit den Bedingungen für die Symmetrielinie des Strahls skaliert werden. Die Erneuerungsfrequenz für den Impuls wird aus Meßdaten ermittelt. Zur Bestimmung der Frequenz für die Erneuerung thermischer Energie wird ein verschobenes Temperaturspektrum angenommen, welches mit experimentellen Daten übereinstimmt. Insgesamt erweist sich die Verwendung des Oberflächen-Erneuerungsmodells im Auftreffgebiet als interessanter alternativer Ansatz für die Berechnung der Oberflächen-Wechselwirkungen.

ПРИМЕНЕНИЕ МОДЕЛИ ВОССТАНОВЛЕНИЯ ДЛЯ ОПИСАНИЯ ТЕПЛОПЕРЕНОСА В ПАДАЮЩЕЙ СТРУЕ

Аннотация—С использованием концепции восстановления применительно к падающей на поверхность нагретой плоской струе определяется распределение локальных коэффициентов теплопереноса на участке соударения. Моделирование базируется на зональном подходе к внешнему течению и участку соударения. Течение во внешней области описывается с помощью стандартной k–ε модели. Участок соударения моделируется с использованием концепции восстановления. Решение на основе предложенной модели зависит от подбора зон и начальных условий. Полученные результаты очень хорошо согласуются с экспериментальными данными при использовании условий на оси струи для процесса восстановления начальной скорости и температуры. Частота восстановления для импульса находится по экспериментальным данным. Восстановление тепловой энергии моделируется на основе частоты восстановления, найденной с учетом смещенного температурного спектра, согласующегося с экспериментальными данными. Показано, что использование модели восстановления на участке соударения струи с поверхностью является эффективным альтернативным методом определения поверхностных взаимодействий.