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PRESENT STATE AND FUTURE OF INFRARED SIGNATURE MODELS

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ABSTRACT

Over the last five years, the two primary signature codes used for ground target modeling have been GTSIG and PRISM. Both codes have had extensive development activities and received wide community support. Although both GTSIG and PRISM utilize nodal networks and finite differencing techniques, each code has specific attributes as well as certain limitations. In addition, target models developed for one code are not compatible with the other code thus resulting in a redundant database in the military community.

GTSIG and PRISM are compared and contrasted in several areas which include: numerical solution techniques (e.g. explicit, implicit, steady state, transient); radiosity models (e.g. diffuse, specular, BRDF, spectral, band averaged); and their user interfaces (e.g. generalized target application, specific component models, pre-processor modeling aids, plume compatibility, graphical display).

Clearly, if all of the attributes of each code were combined into a super code, the result would be a highly versatile modeling tool with fewer limitations and a combined common database of target models. The agencies that now provide funding support for the individual codes would see both an immediate cost benefit from the pooling of resources and the first step towards a common software tool in the ground modeling community. The future development plan for a new enhanced PRISM with downward compatibility for previous GTSIG and PRISM target models is outlined.

INTRODUCTION

The simplest representation of the thermal model as used in infrared signature predictions consists of two core modules: the diffusion module and the radiosity module. In order to provide an overall comparison of thermal models, the generalized governing equations will first be presented followed by specific algorithms found in the actual numerical implementation of GTSIG and PRISM.

The thermal diffusion equation provides a solution to the basic energy balance on a volume. The output is simply the physical temperature for a single volume and a spatial temperature distribution for a set of interconnected volumes or nodes. This set of interconnected nodes comprise the target and its background (i.e., terrain and sky). The fully generalized diffusion equation would include differential heat transfer (i.e., conduction) in three dimensions of space, internal heat sources, and a heat storage term as a derivative of time. When the appropriate boundary conditions are added, the temperature distribution and thus the heat rates can be calculated. The multi-modal boundary conditions include radiation, convection, heat fluxes, contact interfaces, phase change, etc. The generalized equation as represented in its differential form is

$$\frac{d}{dx}\left(k_x \frac{dT}{dx}\right)+\frac{d}{dy}\left(k_y \frac{dT}{dy}\right)+\frac{d}{dz}\left(k_z \frac{dT}{dz}\right)+ Q = r\, C_p\left(\frac{dT}{dt}\right) \tag{1}$$

The radiosity equation calculates the rate at which radiant energy leaves a surface based on its self emission and reflection components. The self emission is calculated directly by its physical temperature and emissivity. The reflection quantity is calculated by its incident irradiation and reflectivity. Since the irradiation consists of all elements, N, in the target-background scene which are all capable of interacting with one another (i.e., multiple bounce), an NxN matrix solution is formed. The radiosity J for N surfaces (i and j=1 | N) is represented by the sum of the emission term and reflection term:

$$J_i = e_i E_{b\,i} + r_i \sum_{j=1}^{N} F_{i\,j}\; J_j \tag{2}$$

All infrared signature models will be based on the above expressions. The actual numerical solutions that are incorporated will result in the variability and the degree of rigor among the models by which they can be discerned through a comparison of their features.

PRESENT STATUS

There has been a significant effort made to date in developing specific application signature codes by government, industry, and academia. There has also been various attempts at consolidating efforts through working groups, code consortiums, and large government funded programs. A joint meeting between the Intelligence Community Modeling Group (ICMG) and the Threat Target Signatures Subgroup (TTSS), which is an activity of JTCG/ME Smart Munitions Working Group (SMWG), was held in September 1991 in which five IR Codes were presented and discussed. This study group produced Table 1 which provides a general comparison of the basic features among the five predictive codes. A general discussion of some the basic features of an infrared signature code will follow.

Table 1 General Comparison of Existing Codes [a]

IR CODES	GTSIG	PRISM	IRMA	SIRIM	SPIRITS
PLUMES	YES	NO	NO	NO	YES
TARGET/ BACKGROUND INTERACTIONS	YES	YES	YES	NO	YES
TIME VARIANT HEAT SOURCES	YES	YES	YES	YES	YES
THREE-DIMENSION	YES	YES	NO	YES	NO[1]
CONDUCTION	YES	YES	NO	YES	NO[1]
INTERNAL CONVECTION	YES	YES	NO	YES	NO[1]
OBJECT-OBJECT RADIATION	YES	YES	YES	NO	YES
MODULAR	YES	YES	YES	YES	YES
GOV'T ACCESS TO SOURCE CODE	YES	YES	YES	YES	YES
TARGETS[2]	RW,GT	GT	GT	GT	FW

[1] yes if GTSIG modules are used
[2] RW-ROTARY WING GT-GROUND TARGETS FW-FIXED WING
[a] Compiled by the Threat Target Signature Subgroup of JTCG/ME in Sept. 1991.

Basic Features

Thermal Diffusion The solution to the energy balance for a volume element (or node) can be stated in words as: the net energy rate to the node is equal to the heat stored, or mathematically as:

$$\Sigma\ Q_i = m_i\, C_p \left(\frac{d\, T_i}{dt} \right) \tag{3}$$

The heat rate terms include all mechanisms of heat transfer with the node: radiation, convection, and conduction. If this equation were solved with an explicit numerical solution where all of the Q's are either imposed heat sources or are based on the temperatures of the previous time step, the new temperature T_i' is then calculated directly from the algebraic solution:

$$T_i{}' = T_i + \frac{\Delta t}{m_i\, C_p} \Sigma Q_i \tag{4}$$

The heat rate terms Q that are functions of T_i can be reformulated as an effective conductance times the temperature difference between node i and j as follows:

$$Q_i = C_{ij}\ \left(T_j - T_i\right) \tag{5}$$

and the effective conductances C_{ij} include conduction C_{ij}=kA/R, convection C_{ij}=hA_i, and radiation $C_{ij}=\sigma\,\ddot{o}_{ij}A_i(T^2_j+T^2_i)(T_j+T_i)$ where T_i, T_j are temperatures from the previous time step. Note that the pseudo-linearized radiation conductance when multiplied by (T_j-T_i) yields the more familiar $Q=\sigma\,\ddot{o}_{ij}A_i(T^4_j-T^4_i)$. Other heat rates (that are not functions of T) such as solar incident radiation or internal sources are simply treated as imposed heat sources and are added directly to the sum of the Q's.

By formulating the problem into effective conductances and imposed heat sources, an implicit solution can be applied. The implicit solution is unconditionally stable since it utilizes the new temperatures TN in its current time step temperature computation. It requires a matrix or iterative solution at each new time step to solve the NxN matrix for temperature. In spite of the increased complexity in problem formulation and additional internal computations, the implicit formulation will often result in a faster solution with higher accuracy than the explicit solution. A recent implementation of the implicit method into PRISM resulted in an order of magnitude increase in speed [1]. GTSIG has utilized an implicit solution from its conception. The implicit difference expression is

$$\frac{m_i C_p}{\Delta t}(T_i{}' - T_i) = \sum_{j=1}^{N}\left[\ C_{ij}\left(\frac{T_j{}' + T_j}{2} - \frac{T_i{}' - T_i}{2}\right)\right] + Q_i \tag{6}$$

and solving for T_iN results in

$$T_i{}' = \frac{\left[\sum_{j=1}^{N} C_{ij} T_j + \sum_{j=1}^{N} C_{ij} T_j{}' + 2Q_i - T_i \sum_{j=1}^{N} C_{ij}\left(1 - \frac{2\, m_i C_p}{\Delta t \sum_{j=1}^{N} C_{ij}}\right)\right]}{\sum_{j=1}^{N} C_{ij}\left(1 + \frac{2\, m_i C_p}{\Delta t \sum_{j=1}^{N} C_{ij}}\right)} \tag{7}$$

Radiosity Since the infrared signature is characterized by the radiance leaving a body, a practical solution is required for the radiosity matrix equation presented earlier. By precalculating a radiation exchange factor $\ddot{o}_{ij}$ from each view factor F_{ij}, (including area A_i and emissivity g$_i$ of each surface), a simple algebraic solution for radiosity can be used:

$$J_i = e_i E_{bi} + \frac{r_i}{e_i}\sum_{j=1}^{N} \mathrm{-}_{ij}\ E_{bj} \tag{8}$$

The methodology for computing radiation exchange factors is covered in references [2,3]. Note that radiance L for diffuse surfaces is calculated by dividing radiosity J by π.

Both GTSIG and PRISM utilize the basic features presented above as well as many of the advanced features that will be discussed later [2,4]. Table 1 provided a superficial comparison of the leading signature codes. Table 2 provides a more extensive summary of the features found in some of the more advanced signature codes and then presents a checklist and comparison for GTSIG and PRISM.

Table 2 Comprehensive Comparison of GTSIG and PRISM Features

FEATURES	GTSIG	PRISM
Thermal Model Expressed With Finite Difference Equations For A 3-D Nodal Network	YES	YES
Numerical F.D.E. Methodology For Transient Solution	Implicit	Explicit (Implicit[*])
Initialization Scheme For Transient Solution	Steady State	Initial Conditions
Forced and Natural Convection Model	YES	YES
Mass Transfer (Evaporation/Condensation) And Precipitation	YES	NO (YES[*])
Extended Convection Models (Aerodynamic And Fluid Flow)	YES	NO
Engine Models And Specialized Tank Component Node Types	NO	YES
Multiple Bounce Radiometric Solution (Diffuse Or BRDF; Band Average Or Spectral)	YES: BRDF; Band	YES: Diffuse; Band
Shadowing And Multiple Bounce Solar Radiative Thermal Exchange	Shadowing; Single Bounce	Shadowing; Multi-Bounce
Solar Reflections Included In Radiometric Solution	YES	NO
Emissivity Properties For Radiometric Solution (Broadband; Sensor Band; Spectral)	Sensor Band	Broadband
Spectral Radiometric Output	NO: Band Only	NO: Band Only
Spatially Non-Isotropic Sky Radiance	NO: Uniform	NO: Uniform
Geometric Calculations: Shadow And View Factors	Software	Software or Hardware
First Principle Backgrounds	YES	YES
Target-Bckgrnd Interactions (Full:Tgt] Bkg; Partial:TgtZBkg; None)	Partial	Partial
Exhaust Plume Signature: (Internal Code, External Code, None)	External	None
Target Variability (Extensive: Ground, Aircraft, High Value, Ships Or Limited: Ground)	Extensive	Limited
Software Versions For Different Targets Or Operating Systems	Single	Multiple
Graphical Interface For Target Model Development And Display	NO	YES

[*] Included in next release

FUTURE DIRECTIONS

If all of the existing features of PRISM and GTSIG were combined and the nonexistent advanced features were developed, a highly advanced super code would be produced. Some of these key features that should be included in an advanced infrared signature code are described.

Advanced Features

Mass Transfer The transfer of mass will occur at an interface such as an exterior surface exposed to moist air. If the vapor pressure of air, P_{va}, is greater than the saturated vapor pressure, P_{vs}, at the interface surface, a driving potential will produce condensation. The condensation layer will increase until either of two conditions occur: the driving potential goes to zero or the force due to its weight is greater than its surface tension (i.e., condensation still occurs for this condition but the layer doesn't increase). Condensation generally occurs in the morning when the surface temperature is below the dew point of the air (i.e., an equivalent condition to the above). Condensation is a heating process and will increase the surface temperature. As the surface temperature increases and P_{vs} becomes greater than P_{va}, evaporation will occur provided there is a layer of mass to transfer.

The formulation for mass transfer requires an energy balance and a mass balance. The energy balance equates the convective heat transfer of the air and surface to the latent heat rate:

$$Q_i = h\ A_i (T_a - T_i) = \dot{m}\ h_{fg}(T_i) \tag{9}$$

$$m' = m + \dot{m}\Delta t \tag{10}$$

The mass layer is not allowed to grow larger than a maximum value based on surface tension. From mass transfer theory [5], it can be shown that equation 9 can be manipulated to

$$Q_i = \frac{.622\, h_{fg}\, h\, A_i}{P_a\, C_{p,a}} (P_{va} - P_{vs}) \tag{11}$$

$$\dot{m} = \frac{Q_i}{h_{fg}} \tag{12}$$

This formulation will provide a method of treating either evaporation or condensation depending on the driving vapor pressure potential and the existence of a mass layer.

The effects of precipitation are due to the latent heat of evaporation calculated as above and sensible cooling from convective heat transfer of the rain to the surface:

$$Q_i = h_r\ A_i\ (T_t - T_i) \tag{13}$$

$$h_r = (\ r\ v\ C_p\ )_r \tag{14}$$

The rain layer on the surface will also increase (up to a maximum) by equation 10 with the flow rate determined by

$$\dot{m} = (\rho \; v)_r \; A_i \tag{15}$$

Aerodynamic Heating This aerodynamic heating model is patterned after the one proposed by Eckert [6] which calculates the heat transfer to the surface by the equation

$$Q_i = h_{ah} A_i (i_{aw} - i_i) \tag{16}$$

where i_{aw} is the enthalpy of the air evaluated at the adiabatic wall temperature. This term accounts for the frictional heating in the air as it comes to rest on the surface.

The convective heat transfer coefficient h_{ah} in this expression is determined from the appropriate Nusselt number correlation with the Nusselt number for high speed flow being defined as

$$Nu_x = \frac{h_{ah} \, x \, C_{p,a}}{k_a} \tag{17}$$

The adiabatic wall enthalpy can be determined from a knowledge of the free stream enthalpy i_∞, the recovery factor r, and the free stream velocity of the air v_∞ which gives

$$i_{aw} = i_\infty + \frac{r \, v_\infty^2}{2} \tag{18}$$

All properties of the air must be evaluated at a reference temperature that is a function of the Mach number M. The expression for the reference enthalpy i^* is

$$i^* = \frac{i_\infty + i_i}{2} + 0.22 \, r \left(\frac{\gamma - 1}{2} \right) M^2 \, i_\infty \tag{19}$$

and since the enthalpy of the air is only a function of temperature, the reference temperature T^* used to evaluate all air properties in the aerodynamic model is the temperature for which the enthalpy is i^*.

Bidirectional Reflectance The radiosity model is first used during the heat transfer solution for thermal (or broadband) radiation exchange and then is used once more to calculate the band limited radiance (emittance and reflectance) as seen by the designated sensor. The diffuse representation for the thermal radiative exchange provides an expedient solution with high accuracy. This situation is also true for most cases in the band limited radiance calculation. A more complicated and time consuming solution for the band limited radiance would utilize the full bidirectional reflectance distribution function (BRDF) representation of the surface properties which then results in the following integral equation for radiance leaving a surface:

$$\begin{aligned} L_o(\lambda, x, y, \theta_o, \phi_o) &= \varepsilon(\lambda, x, y, \theta_o, \phi_o) \; L_b(\lambda, T(x,y)) \\ &+ \int \rho_{bd}(\lambda, x, y, \theta_o, \phi_o, \theta_i, \phi_i) \; L_i(\lambda, x, y, \theta_i, \phi_i) \cos\theta_i \; d\omega_i \end{aligned} \tag{20}$$

A practical yet rigorous bidirectional radiance solution that utilizes spatially uniform facet properties (directional emissivity and bidirectional reflectivity) and diffuse radiation from other facets and the background is

$$\begin{aligned} L_n(observ) = {} & \varepsilon_n(observ)\, L_{b,N} \\ & + \sum \rho_{bd,n}(observ, ANGnM)\, J_M\, F_{nM} \\ & + \rho_{hd,n}(observ)(1/\pi)\{J_{earth}\, F_{n,earth} + J_{sky}\, F_{n,sky}\} \\ & + \rho_{bd,n}(observ, sun)\, G_{sun}\, VIS(n, sun) \end{aligned} \tag{21}$$

where ***observ***, ***ANGnM***, and ***sun*** are directional vectors and *VIS* is a visibility function [2,7]. Equation 21 can be simplified considerably without significant impact on accuracy by using hemispherical-directional reflectivities rather than full BRDF:

$$\begin{aligned} L_n(observ) = {} & \varepsilon_n(observ)\, L_{b,N} + (1 - \varepsilon_n(observ))/\pi\, \{J_{earth}\, F_{n,earth} \\ & + J_{sky}\, F_{n,sky} + G_{sun}\, VIS(n,sun) + \sum J_M\, F_{nM}\} \end{aligned} \tag{22}$$

Non-Isotropic Sky The uniform sky temperature (blackbody equivalent) based on average sky dome radiance will introduce inaccuracies into the reflection component of the target signature particularly for a non-diffuse surface [8]. A more accurate approach would be to utilize directional sky temperatures, bidirectional reflectivities of the target surfaces, and view factors from the surfaces to the discretized sky dome. Since this approach would be used in a BRDF solution as described above, appropriate surface reflectivities would exist. The directional sky temperature would be calculated by applying a weighting factor A(θ_z) as a function of zenith angle to the average sky irradiance as described in references [2,9]. The view factors are obtained from the previously calculated fractional viewable areas FVA (or commonly called shadow factors). Since the shadow factors are calculated for both azimuth and zenith angle locations at 10° increments and the sky temperature will be specified as a function of zenith angle only, a simple integration (or summation) about the azimuth (0 to 360°) would be done for each target surface producing a view factor from the target surface to an incremental sky dome or ring (i.e., 10° inclination band):

$$F_{n\theta_{z,i}} = 2 \sin \bar{\theta}_{z,i}\; d\theta_{z,i} \sum_{\phi_i = 0}^{360} FVA_{n\phi_i} \tag{23}$$

The reflected component of sky radiance from a target surface L_s is then described as:

$$L_n(observ) = \sum_{\theta_{z,i} = 0}^{90} \rho_{bd,n}(observ, sky)\; E_{b,sky}(\theta_{z,i})\; F_{n\theta_{z,i}} \tag{24}$$

where ***sky*** is an additionally defined sky vector.

Fluid Flow Sophisticated engine models require an advanced fluid flow algorithm. The flow in a general heat engine is caused by: 1) active pressure sources (e.g. pumps, fans, compressors) that produce forced flow; and 2) passive pressure sources (e.g. buoyancy or draft flow) that produce natural flow. The fluid flow is coupled with heat flow in and out of the system. By solving the basic energy, momentum, and continuity equations, the flow rate and thermodynamic conditions can be established for the system of control volumes or flow circuits.

Energy Equation:

$$Q + W_{net} = \dot{m} \int_{c.v.} \left(i + v^2/2 + g\,z \right) \tag{25}$$

Momentum Equation:

$$dP + \rho\, g\, dz + \frac{d(\rho\, v^2)}{2} + \frac{\rho\, v^2}{2} \left(f \frac{d\ell}{D_h} \right) = 0 \tag{26}$$

Continuity Equation:

$$\dot{m} = \rho\, A\, v \tag{27}$$

The engine is modeled as a series of control volumes assembled into a flow circuit. The energy and momentum equations are then solved for each discrete section of the circuit by using finite difference techniques [10].

Extended Radiometric Output The output requirements for an infrared signature model will vary depending on specific application and the capability of the model itself. The basic model would include physical surface temperatures of the target (calculated directly from the diffusion model) and radiometric quantities (calculated from the radiosity model). The radiometric quantities for the target surfaces should include radiance and apparent temperature (also called radiometric or blackbody equivalent temperatures). The target radiance and apparent temperature should be calculated in the sensor band of interest. Signatures are also reported as intensity which is the product of the target radiance and its projected area.

In addition to band-limited radiometric quantities there often is a need for spectral quantities particularly when exhaust plumes are included in the target signature. Fundamentally this does not require any new information, and in effect, band limited quantities are computed from the integration of spectral quantities. Since the signature is composed of an emitted component and several reflected components (e.g. earthshine, skyshine, solar glint, self-reflections, exhaust plume, etc.), it requires much less storage to keep track of the single band-limited quantity versus the multiple spectral quantities. Often tradeoffs are made by using a non-rigorous radiosity model in order to justify spectral quantities. Methods must be utilized that maintain the rigor of the radiosity model while providing a spectral radiometric output.

Graphical User Interface The signature prediction code can be thought of as the computation or core engine of the radiometric analysis. The pre and post processors that will interface with this engine are extremely important for both developing efficient and accurate target models and for proper utilization and display of the radiometric output. It is extremely time consuming to build large nodal network thermal models from “scratch” especially without any graphical support for the geometric representation. A graphical user interface between the geometric configuration and the thermal network provides a visual description and bookkeeping aid to the model developer. In the same sense it is difficult to interpret your results from the analyses with only numerical output. Graphical presentation in the form of synthetic images can provide diagnostic, interpretive, and quantitative output.

Two very advanced preprocessing tools are BRL-CAD [11] for developing solid geometry models and FRED (Faceted Region EDitor) [12] for converting BRL solid models to PRISM thermal models. FRED has also been modified to provide a link to GTSIG and SPIRITS models. Since the geometry model could also originate from other CAD Models (e.g. AutoCAD, CADKEY, PATRAN, etc.), a neutral file format would eliminate the data exchange or translation problems between the geometry model and the thermal model. Rather than creating a direct translator for every geometry model format, a single file format would be preferable such as IGES (Initial Graphics Exchange Specification) [13]. This would provide a systematic method of geometric data exchange in the modeling community.

On the output stream end of the signature code, a graphical interface could provide the user with a visual display of the target signature that would be comparable to the measured radiometric sensor's image. PRISM supports an image based system (IBS) for displaying the radiometric image of the model during processing. This provides a continuously updated image during transient analysis. Further processing of images obtained from FRED/PRISM or GTSIG can be done with TTIM (TACOM Thermal Imaging Model) [14] for providing sensor, atmospheric, and battlefield effects to the image.

Massively Parallel Computation Most of the modeling efforts have been restricted to a single target and background of limited size and interaction. The scenes are typically static, small, and low resolution. An operational scenario may require a large non-homogeneous scene of multiple targets and backgrounds with interactions in both directions (i.e., target also influences background and other target signatures). To provide operational realism, the scenes should be capable of supporting dynamics (e.g. vehicle movement), large spatial or geographic databases, and high resolution. By decomposing the scene model and computational scheme into independent units, a multi-processor computer (or a distributed network of computers) could then solve "pieces" of the model in parallel. Rather than using the traditional procedural programming languages such as Fortran or C, symbolic or object oriented systems utilizing rule-based programming would be more suitable to the task. The autonomous decomposition of the model will provide a means of doing large complex systems as well as real time simulation for automatic target recognizers (ATR).

Extended Database

Since both GTSIG and PRISM have had several years of continuous government support, a combined code would produce a comprehensive common database that is available to the community through approval from the sponsoring agency. This inventory contains a variety of target and background types for both military and commercial infrared applications.

Table 3 Sample Target Inventory For PRISM/GTSIG Compatible Code

GROUND VEHICLES	HIGH VALUE	AIRCRAFT	OTHER	BACK GROUNDS
T-62	DAM	F-4	NAVY SHIP	SOIL TERRAIN
T-72	POL TANK	C-130	KRIVAK SHIP	WATER
T-80	BUNKER	F-15	SCUD	SNOW
ZIL-157	BRIDGE	RC-12K	SA-12	FOLIAGE
ZSU-23-4	STEEL PLANT	AH-64A	CAMO NET	CONCRETE
M-1	HYDRO PLANT	LONGBOW		ASPHALT
M-2	REFINERY	MH-53J		TREE
BMP-2	BUILDING	HIND D		
BRDM-2	RAILROAD	HAVOC		
M-60	AIRFIELD	HOKUM		
M-113		LHX		
PATRIOT GENERATOR		CH-47D		
ARMY GENERATOR		OH-58D		
		UH-60L		
		MH-60K		

SUMMARY

Presently there are many specific application codes which has resulted in a large database of either noncompatible or redundant target models. The need for a universal signature code is there. The algorithms and requirements for an advanced signature code have been presented. The expertise exists in the modeling community. The consolidation of GTSIG and PRISM will be the first step towards realizing this goal.

NOMENCLATURE

Symbols

A = area, m^2
C_{ij} = conductance, W/K
C_p = specific heat, J/kg-K
D_h = hydraulic diameter, m
E_b = blackbody emissive power, W/m^2
F = view factor
ö = radiation exchange factor
f = friction factor
G_{sun} = direct solar load, W/m^2
g = gravitational acceleration, m/s^2
h = convective coefficient, W/m^{2-}K
h_{ah} = aerodynamic heating coefficient, kg/s-m^2
h_{fg} = latent heat of evaporation, J/kg
i = enthalpy, J/kg
J = radiosity, W/m^2
k = thermal conductivity of node,W/m-K
L = radiance, W/m^{2-}sr
R = node or control volume length, m
m = mass, kg
mdot = mass flow rate, kg/s
M = Mach number
P = pressure, mbar
P_{va} = vapor pressure of air, mbar
P_{vs} = sat. vapor pressure at surf. temp., mbar
Q = heat rate, W
r = recovery factor
T = temperature, EK or EC
t = time, s
Δt = time step, s
v = velocity at time t, m/s
W_{net} = work rate, W
x = distance from stagnation point, m
z = elevation, m

Greek

ε = emissivity
γ = ratio of specific heats of air
θ = polar angle, degrees
θ_z = sky zenith angle, degrees
ϕ = azimuthal angle, degrees
$d\omega$ = differential solid angle, steradians
λ = wavelength, μm
ρ = mass density of node, kg/m^3, or
ρ = reflectivity, as determined by its context
σ = Stefan-Boltzmann constant, W/m^{2-}K^4

Superscript

N = new time
* = reference state

Subscripts

a = air
ah = aero heating
aw = adiabatic wall
b = blackbody
bd = bidirectional
hd = hemispherical-directional
i,o = incoming, outgoing
i,j = surface or nodal indices
N,M = target nodes
n = target facet
r = rain
v = volume
x,y,z = surface coordinates
4 = free stream

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