NUMERICAL STUDY ON HYPERSONIC FLOW OVER A FORE-BODY WITH SHALLOW CAVITY

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Contents

Introduction

- Studies of momentum and thermal transport characteristics in rarefied gas flow over a hypersonic vehicle are important due to their applications in aerospace engineering.
- The interaction of gas molecules with solid surface boundary is the origin of momentum and energy transfer subjected by the solid surface from the gas flow.
- A better understanding of the influences of the gas-surface interaction model in hypersonic flow simulations is thus expected to be very desirable on the better design and performance of the relevant flight vehicles.

Introduction (Continue)

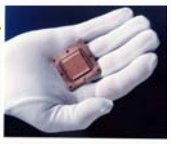
- In this study, the DSMC method is adopted to implement the three dimensional computations of the hypersonic rarefied flow over a missile fore-body with optical window.
- Two kinds of thermal boundary conditions are considered. One is CLL model with various accommodation coefficients for isothermal wall, and the other is IS (Isotropic Scattering) model for adiabatic wall.
- The major concern is the analysis of aero-thermal properties in the hypersonic three dimensional shallow cavity flow affected by varying flight angle of attack and wall boundary conditions.

Introduction

***Kn**udsen Number*

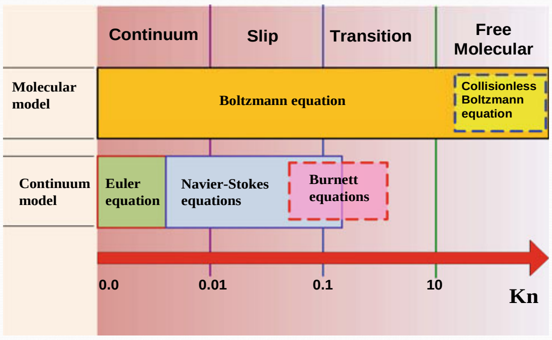
$\frac{\lambda}{L}$

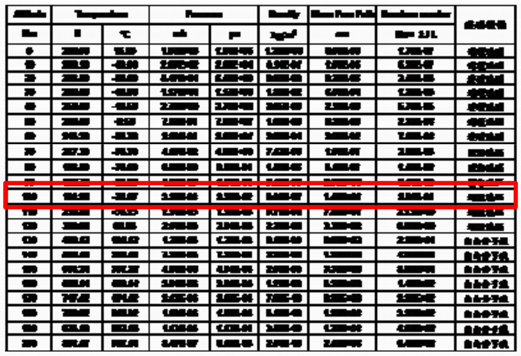
Satellite (QuickBird)
http://www.richitech.com.tw/



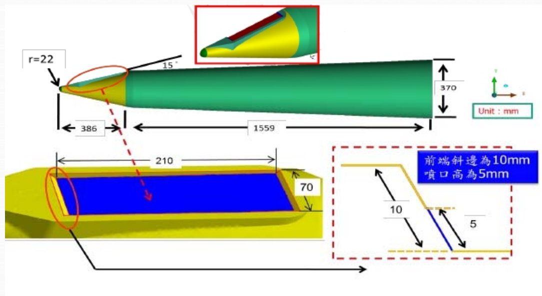
Microchannel heat exchanger
http://core.materials.ac.uk/

Flow Regimes in terms of Kn





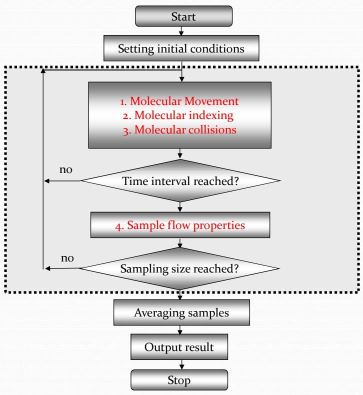
Problem Description



Conditions of Simulation

Parameters	Numbers	Units
Height	100	km
Temperature	194	K
Wall Temperature	1000	K
Density	5.5824×10^{-7}	kg/m^3
Number density	1.1898×10^{19}	m^{-3}
Velocity	2799	m/s
Mach numbers	10	

Numerical Method (DSMC)



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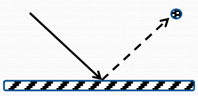
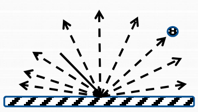
Solid boundary condition

- Maxwell Model

Specular reflection



Diffuse reflection

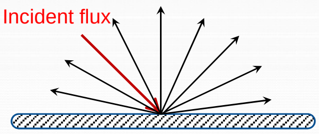


Accommodation Coefficient

The accommodation coefficient of molecular property Q is defined in terms of incident and reflected fluxes as follows:

$$QAC = (Q_i - Q_r)/(Q_i - Q_w)$$

Solid boundary condition



Isotropic Model

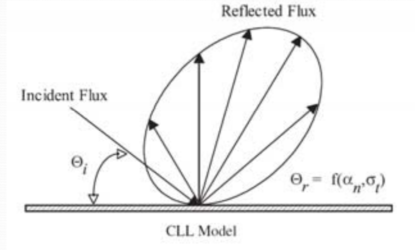
$$|\vec{C}| = |\vec{C^*}|$$

$$u^* = \left(|\vec{c}|(1-R_{f1})^{\frac{1}{2}}\right)\cdot\cos(2\pi\cdot R_{f2})$$

$$v^* = -|\vec{c}|(R_{f1})^{\frac{1}{2}}$$

$$w^* = \left(|\vec{c}|(1-R_{f1})^{\frac{1}{2}}\right)\cdot\sin(2\pi\cdot R_{f2})$$

Solid boundary condition



$$\alpha_n = \frac{e_i - e_r}{e_i - e_w}$$

$$\sigma_t = \frac{\tau_i - \tau_r}{\tau_i}$$

Cercignani-Lamps-Lord Model

Cercignani-Lamps-Lord (CLL) Model

- Experimental results show that molecules reflected from solid surfaces present lobular or pedal-like distributions and are poorly represented by the Maxwell model. A phenomenological model that has demonstrated improvement over the Maxwell model was proposed by Cercignani, Lampis and Lord.
- Cercignani, Lampis and Lord (CLL) model based on the definition of the coefficients α_n and σ_t that represent the accommodation coefficients of normal component of translational energy and the tangential component of momentum, respectively. The CLL model produces physically more realistic distributions for the re-emitted molecules

Algorithm equations for CLL Model

$$U_n^* = -|Vmp|\begin{pmatrix} R_n^2 + (1-\alpha_n)\cdot\left(\frac{U_n}{Vmp}\right)^2 + \\ 2\cdot R_n(1-\alpha_n)^{1/2}\left(\frac{U_n}{Vmp}\right)\cos(2\pi R_{f2}) \end{pmatrix}^{1/2}$$

$$R_n = \left(-\alpha_n \ln R_{f1}\right)^{1/2}$$

$$U_{t2}^* = |Vmp|\left(U_{t1}^*\big|_{ang}\cos(\phi) + U_{t2}^*\big|_{ang}\sin(\phi)\right)$$

$$U_{t1}^* = |Vmp|\left(U_{t1}^*\big|_{ang}\cos(\phi) - U_{t2}^*\big|_{ang}\sin(\phi)\right)$$

$$\phi = \arctan\left(\frac{U_{t2}}{U_{t1}}\right)$$

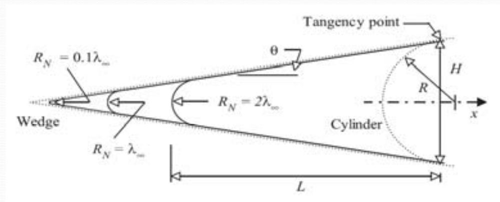
$$U_{t1}^*\big|_{ang} = R_t\cdot\cos(2\pi R_{f4}) + (1-\alpha_t)^{1/2}\cdot\frac{(U_{t1}^2 + U_{t2}^2)^{1/2}}{Vmp}$$

$$U_{t2}^* = R_t\cdot\sin(2\pi R_{f4})$$

$$R_t = (-\alpha_t \ln R_{f3})^{1/2}, \quad \alpha_t = \sigma_t(2-\sigma_t)$$

Results and Discussion

Verification

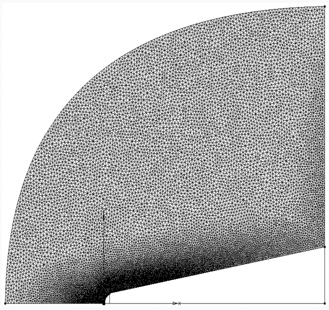


$$ds = \sqrt{dx^2 + dy^2}$$

$$s = \int_{x=a}^{x=b} ds$$

$$S = s/\lambda_\infty$$

θ	R	λ_∞	L
10°	5mm	0.903mm	24.12mm



Tetrahedral	0
Hexahedral	0
Pyramid	0
Prism	31,339
Total Cells	**31,339**
Total Points	**32,010**

Simulation conditions

Parameters	Numbers	Units
Height	70	km
Temperature	220	K
Wall Temperature	880	K
Density	8.753×10^{-5}	kg/m^3
Number density	1.8209×10^{21}	m^{-3}
Velocity	3560	m/s
Mach numbers	12	

Heat Transfer Coefficient

$$C_h = \frac{q_w}{\rho_\infty V_\infty^3 / 2}$$

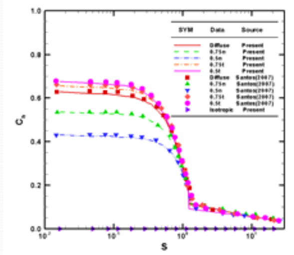
Pressure Coefficient

$$C_p = \frac{p_w - p_\infty}{\rho_\infty V_\infty^2 / 2}$$

Skin Friction Coefficient

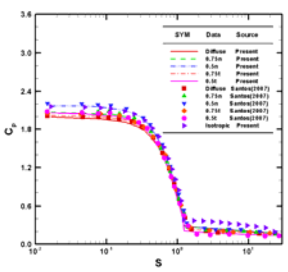
$$C_f = \frac{\tau_w}{\rho_\infty V_\infty^2 / 2}$$

Heat Transfer Coefficient



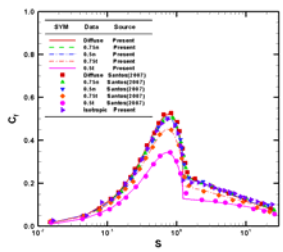
C_h	Santos(2007)	Present
Diffuse	0.630	0.6283
$\alpha_n = 0.75, \sigma_t = 1$	0.537	0.5356
$\alpha_n = 0.5, \sigma_t = 1$	0.429	0.4318
$\alpha_n = 1, \sigma_t = 0.75$	0.660	0.6567
$\alpha_n = 1, \sigma_t = 0.5$	0.676	0.6759

Pressure Coefficient



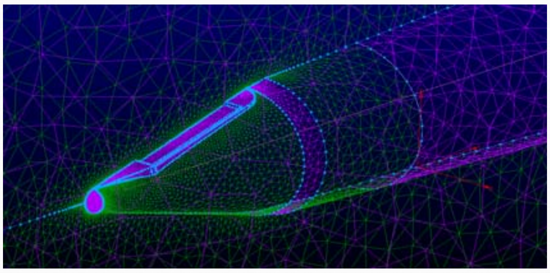
C_p	Present
Diffuse	1.993
$\alpha_n = 0.75, \sigma_t = 1$	2.068
$\alpha_n = 0.5, \sigma_t = 1$	2.170
$\alpha_n = 1, \sigma_t = 0.75$	2.021
$\alpha_n = 1, \sigma_t = 0.5$	2.058
Isotropic	2.159

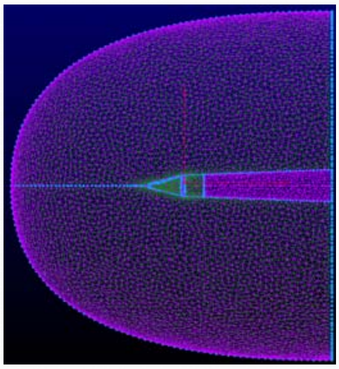
Skin Friction Coefficient



C_f	Present
Diffuse	0.5271
$\alpha_n = 0.75, \sigma_t = 1$	0.5133
$\alpha_n = 0.5, \sigma_t = 1$	0.5045
$\alpha_n = 1, \sigma_t = 0.75$	0.4525
$\alpha_n = 1, \sigma_t = 0.5$	0.3438
Isotropic	0.5022

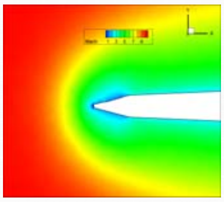
3D grid system for missile forbody with optical window



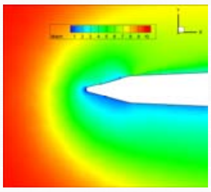


Tetrahedral	357,528
Hexahedral	0
Pyramid	0
Prism	0
Total Cells	**357,528**
Total Points	**67,848**

Mach number distribution

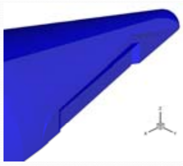


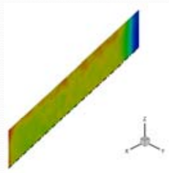
$\alpha_0 = 0°$

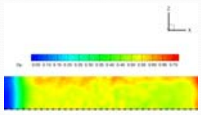


$\alpha_0 = 10°$

Distribution of Pressure Coefficient on Cavity Surface







Simulation conditions

Parameters	Numbers	Units
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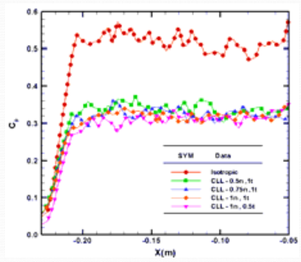
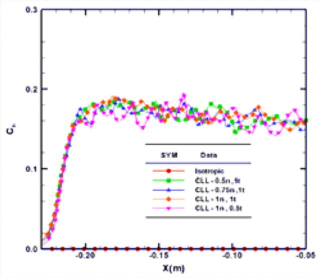
Density	5.5824×10^{-7}	kg/m^3
Number density	1.1898×10^{19}	m^{-3}
Velocity	2799	m/s
Mach numbers	10	

Stream-wise distributions of C_p for different gas-surface interactions model on the plane of symmetry



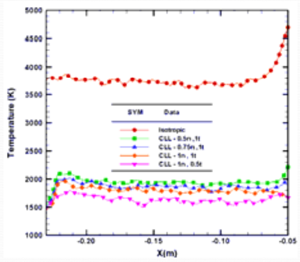
$\alpha_0 = 0°$

Stream-wise distributions of C_h for different gas-surface interactions model on the plane of symmetry



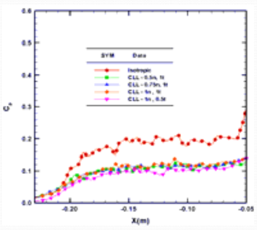
$\alpha_0 = 0°$

Stream-wise distributions of temperature for different gas-surface interactions model on the plane of symmetry

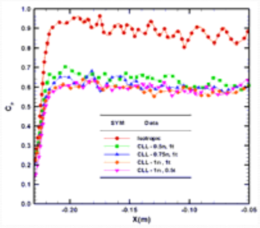


$\alpha_0 = 0°$

Stream-wise distributions of C_p for different gas-surface interactions model on the plane of symmetry

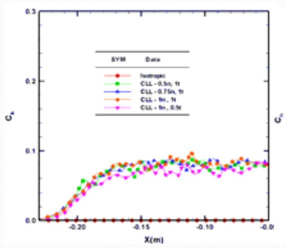


$\alpha_0 = 10°$

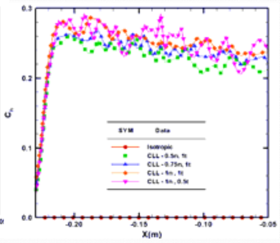


$\alpha_0 = -10°$

Stream-wise distributions of C_h for different gas-surface interactions model on the plane of symmetry

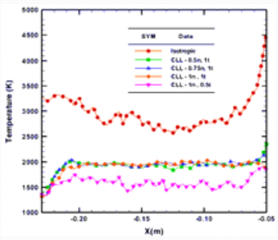


$\alpha_0 = 10°$

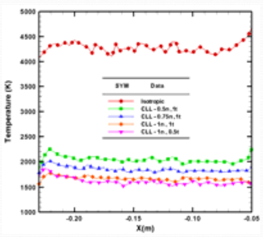


$\alpha_0 = -10°$

Stream-wise distributions of temperature for different gas-surface interactions model on the plane of symmetry



$\alpha_0 = 10°$



$\alpha_0 = -10°$

Conclusions

- The pressure coefficient, heat flux coefficient and temperature along the bottom surface of shallow cavity are all found to be increased with decreasing angle of attack. This can be due to the enhanced compression effect on the upper part of forebody.
- The overall value of pressure coefficient along the surface of shallow cavity for adiabatic wall is higher than that for isothermal wall. Both pressure and heat flux coefficients do not show much change as varying accommodation coefficients in CLL model.
- The simulated temperature distribution of optical window in IS model for adiabatic wall can be as high as about 2800 to 4300 K. It seems that cooling devices to protect optical window system may have to be provided.