

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

Pei-Yuan Tzeng
National Defense University, Taiwan
ISTP-26, Sep. 30, 2015, Leoben

Contents

- Introduction
- Problem Description
- Numerical Method
- Results and Discussion
- Conclusions

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



$\frac{\lambda}{L}$

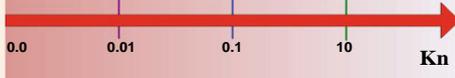


Satellite (QuickBird)
<http://www.fhitech.com.tw/>

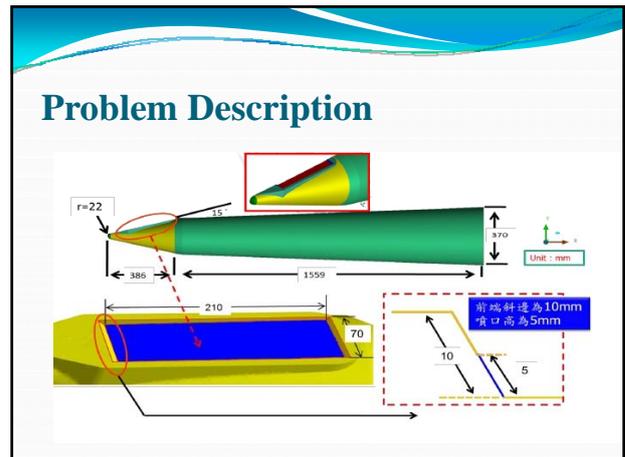


Microchannel heat exchanger
<http://core.materials.ac.uk/>

Flow Regimes in terms of Kn

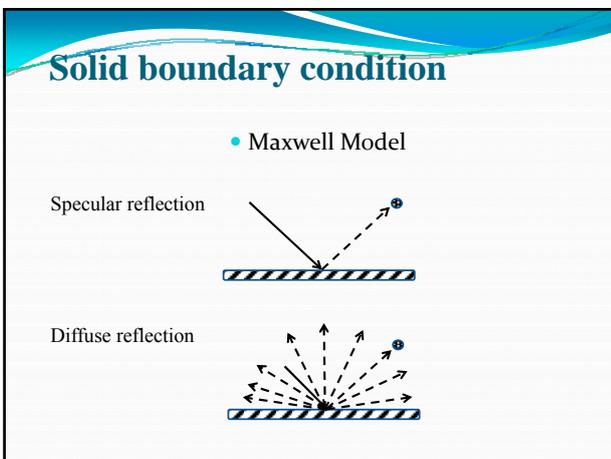
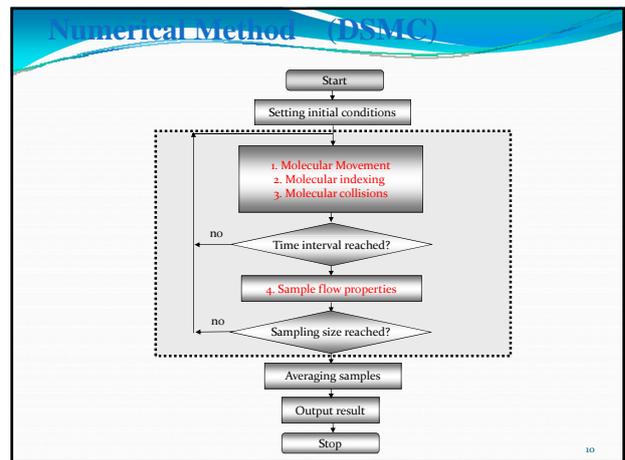
	Continuum	Slip	Transition	Free Molecular
Molecular model	Boltzmann equation			Collisionless Boltzmann equation
Continuum model	Euler equation	Navier-Stokes equations	Burnett equations	
				
	0.0	0.01	0.1	10
	Kn			

Altitude	Temperature	Pressure	Density	Mean Free Path	Mean free number	自由程
km	°C	Pa	kg/m ³	m	1/m	mm
0	20.00	1.01325e5	1.22500	6.61e-08	1.51e+07	0.0635
10	216.65	2.47757e4	2.36157	4.50e-07	2.23e+06	0.4478
20	270.65	5.02651e3	1.65443	1.51e-06	6.59e+05	1.5329
30	310.65	7.38406e2	1.06679	4.50e-06	2.23e+05	4.4780
40	339.65	9.59648e1	6.84932e-01	1.51e-05	6.59e+04	15.3290
50	358.65	1.16876e1	4.46089e-01	4.50e-05	2.23e+04	44.7800
60	368.65	1.36589e0	2.89531e-01	1.51e-04	6.59e+03	153.2900
70	370.65	1.55203e0	1.87546e-01	4.50e-04	2.23e+03	447.8000
80	364.65	1.71763e0	1.25362e-01	1.51e-03	6.59e+02	1532.9000
90	342.65	1.85283e0	8.17006e-02	4.50e-03	2.23e+02	4478.0000
100	305.65	1.96875e0	5.25287e-02	1.51e-02	6.59e+01	15329.0000
110	254.65	2.05623e0	3.17683e-02	4.50e-02	2.23e+01	447.8000
120	199.65	2.11529e0	1.87546e-02	1.51e-01	6.59e+00	15.3290
130	141.65	2.14584e0	1.11155e-02	4.50e-01	2.23e+00	4.47800
140	80.65	2.14789e0	6.46239e-03	1.51e+00	6.59e-01	1.53290
150	18.65	2.13146e0	3.99688e-03	4.50e+00	2.23e-01	0.44780
160	-43.35	2.09755e0	2.36157e-03	1.51e+01	6.59e-02	0.15329
170	-105.35	2.04627e0	1.41471e-03	4.50e+01	2.23e-02	0.04478
180	-176.35	1.97761e0	8.30868e-04	1.51e+02	6.59e-03	0.01533
190	-256.35	1.89251e0	4.84983e-04	4.50e+02	2.23e-03	0.00448
200	-345.35	1.79281e0	2.74557e-04	1.51e+03	6.59e-04	0.00153
210	-443.35	1.67941e0	1.56741e-04	4.50e+03	2.23e-04	0.00045
220	-550.35	1.55321e0	8.93683e-05	1.51e+04	6.59e-05	0.00015
230	-666.35	1.41521e0	5.11253e-05	4.50e+04	2.23e-05	4.5e-05
240	-791.35	1.26721e0	2.89531e-05	1.51e+05	6.59e-06	1.5e-05
250	-924.35	1.11121e0	1.65443e-05	4.50e+05	2.23e-06	4.5e-06
260	-1064.35	9.48221e-01	9.45633e-06	1.51e+06	6.59e-07	1.5e-06
270	-1210.35	7.79721e-01	5.40083e-06	4.50e+06	2.23e-07	4.5e-07
280	-1361.35	6.06821e-01	3.06593e-06	1.51e+07	6.59e-08	1.5e-07
290	-1517.35	4.30821e-01	1.73643e-06	4.50e+07	2.23e-08	4.5e-08
300	-1678.35	2.52321e-01	9.83243e-07	1.51e+08	6.59e-09	1.5e-08



Conditions of Simulation

Parameters	Numbers	Units
Height	100	km
Temperature	194	K
Wall Temperature	1000	K
Density	5.5824 x10 ⁻⁷	kg/m ³
Number density	1.1898 x10 ¹⁹	m ⁻³
Velocity	2799	m/s
Mach numbers	10	

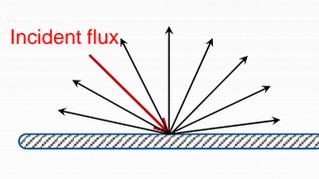


Accommodation Coefficient

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



Incident flux

Isotropic Model

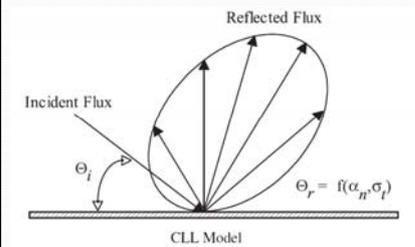
$$|\bar{c}| = |\bar{c}'|$$

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

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

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

Solid boundary condition



Reflected Flux

Incident Flux

Θ_i

$\Theta_r = f(\alpha_r, \sigma_r)$

CLL Model

Cercignani-Lamps-Lord Model

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

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

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_i 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

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

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

$$U_{i2}^* = |Vmp| \left(U_{i1}^* \cos(\phi) + U_{i2}^* \sin(\phi) \right)$$

$$U_{i1}^* = |Vmp| \left(U_{i1}^* \cos(\phi) - U_{i2}^* \sin(\phi) \right)$$

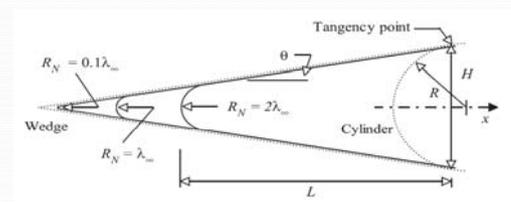
$$\phi = \arctan \left(\frac{U_{i2}}{U_{i1}} \right)$$

$$U_{i1}^* \Big|_{\text{lang}} = R_i \cdot \cos(2\pi R_{f4}) + (1 - \alpha_i)^{\frac{1}{2}} \cdot \left(\frac{U_{i1}^2 + U_{i2}^2}{Vmp} \right)^{\frac{1}{2}}$$

$$U_{i2}^* = R_i \cdot \sin(2\pi R_{f4}) \quad R_i = (-\alpha_i \ln R_{f3})^{\frac{1}{2}}, \quad \alpha_i = \sigma_i (2 - \sigma_i)$$

Results and Discussion

Verification



Tangency point

$R_N = 0.1\lambda_\infty$

$R_N = \lambda_\infty$

$R_N = 2\lambda_\infty$

Wedge

Cylinder

L

H

R

θ

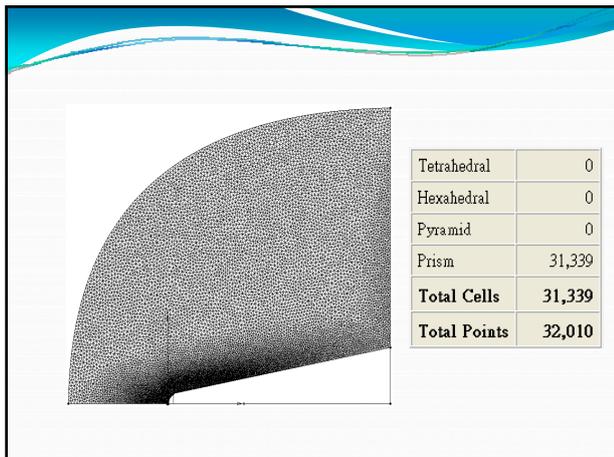
x

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

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

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

θ	R	λ_∞	L
10°	5mm	0.903mm	24.12mm



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

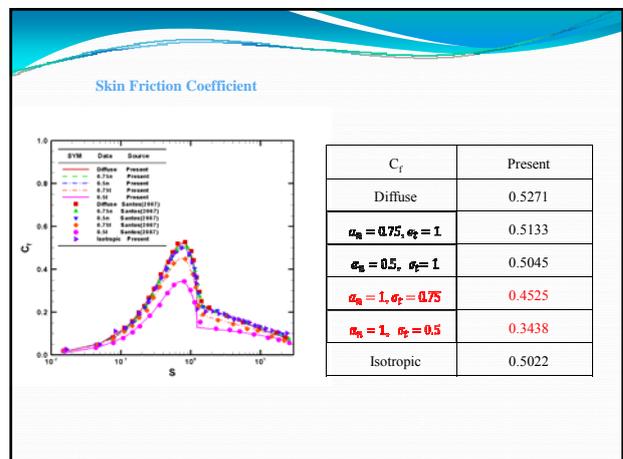
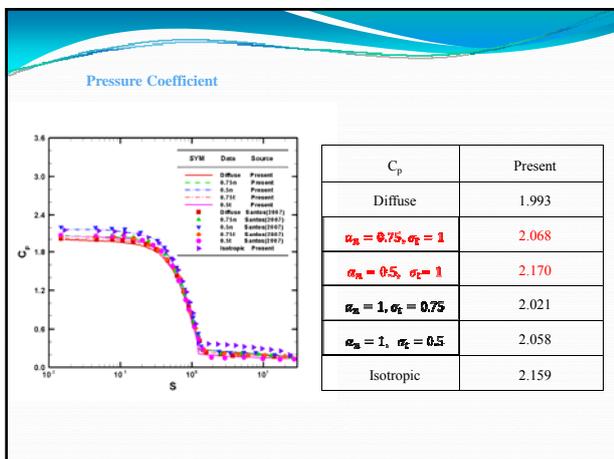
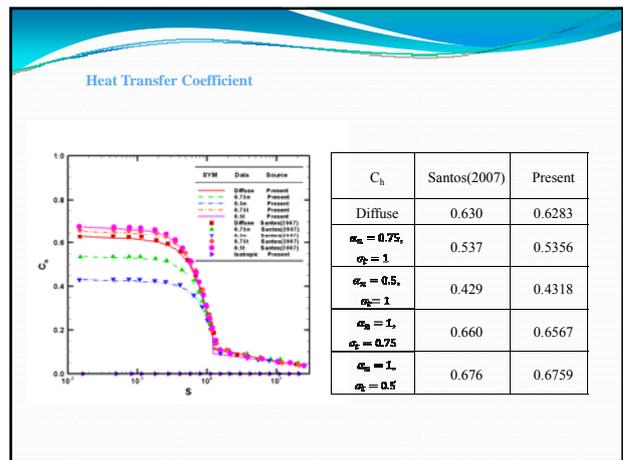
$$C_h = \frac{q_w}{\rho_\infty V_\infty^3 / 2}$$

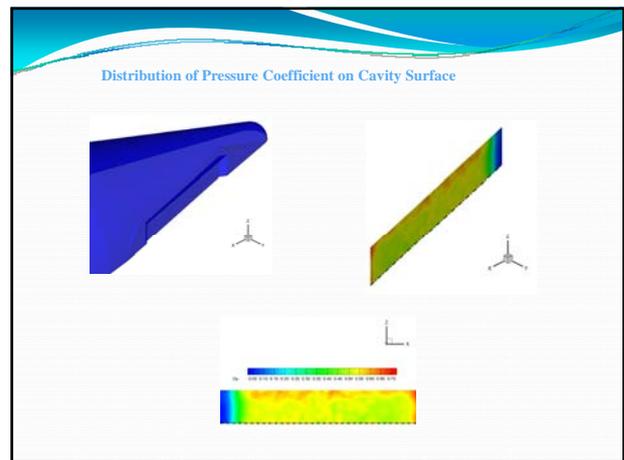
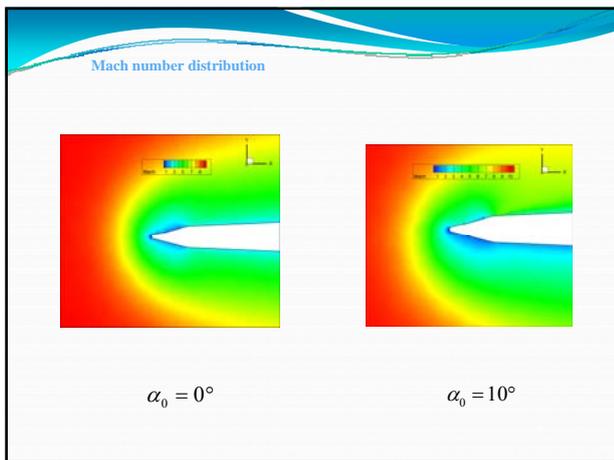
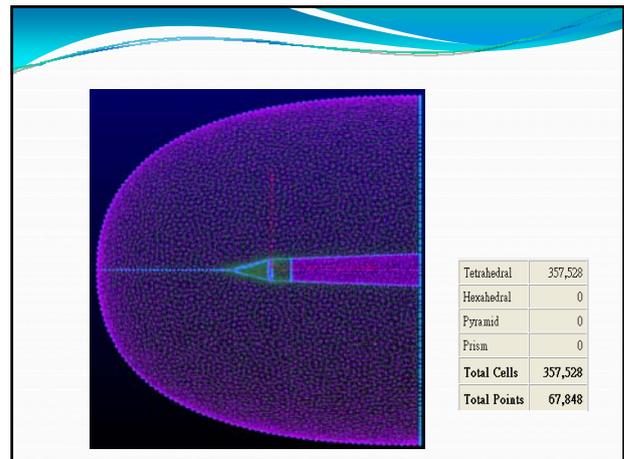
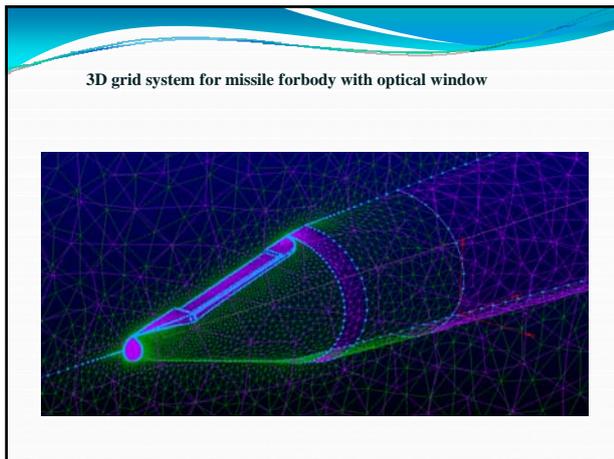
Pressure Coefficient

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

Skin Friction Coefficient

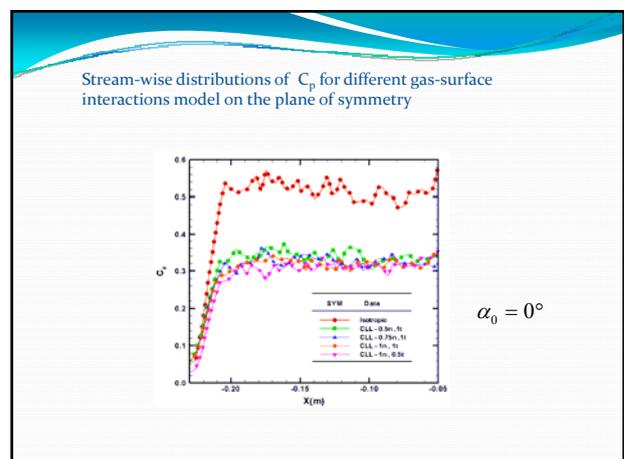
$$C_f = \frac{\tau_w}{\rho_\infty V_\infty^2 / 2}$$

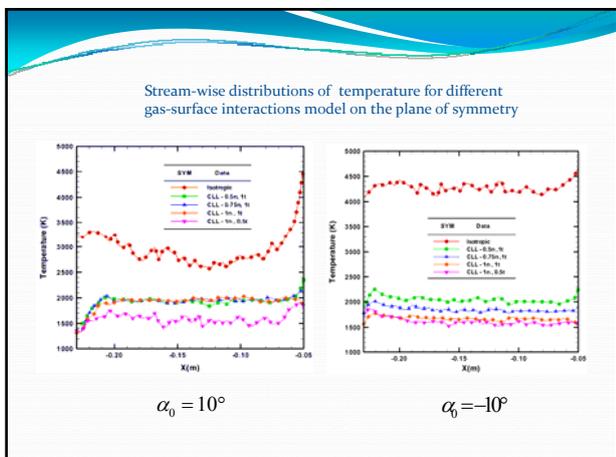
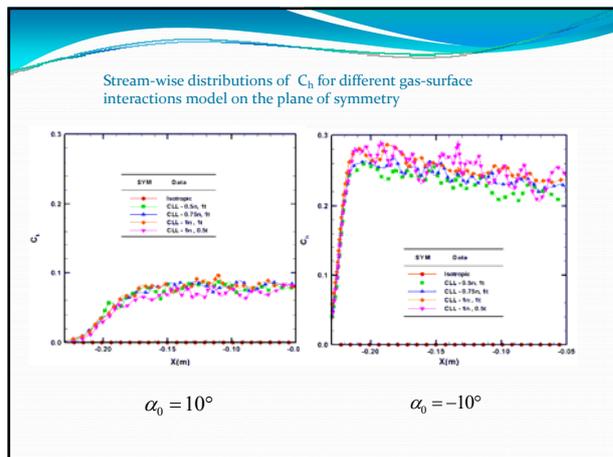
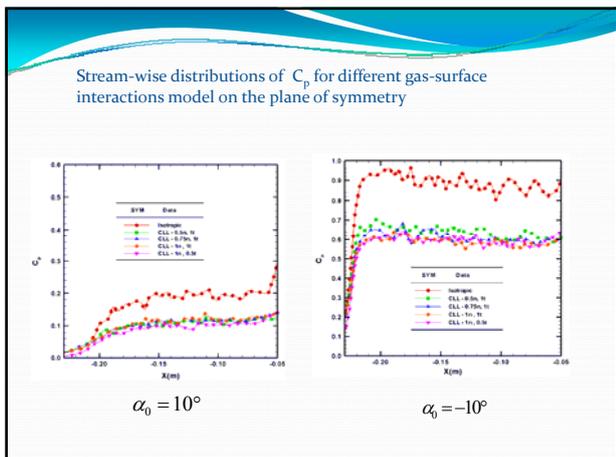
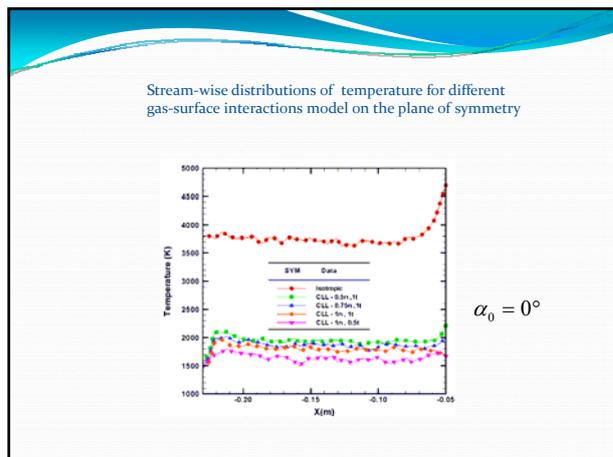
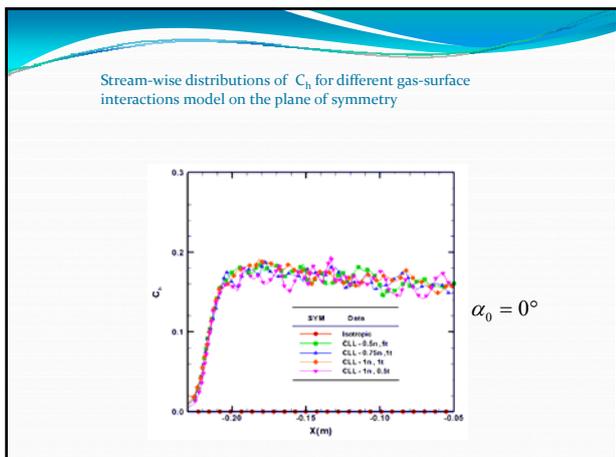




Simulation conditions

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	





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.