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OMICS Group International is a pioneer and leading science event organizer, which publishes around 400 open access journals and conducts over 300 Medical, Clinical, Engineering, Life Sciences, Pharma scientific conferences all over the globe annually with the support of more than 1000 scientific associations and 30,000 editorial board members and 3.5 million followers to its credit.

OMICS Group has organized 500 conferences, workshops and national symposiums across the major cities including San Francisco, Las Vegas, San Antonio, Omaha, Orlando, Raleigh, Santa Clara, Chicago, Philadelphia, Baltimore, United Kingdom, Valencia, Dubai, Beijing, Hyderabad, Bengaluru and Mumbai.

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Washington University in St.Louis

Shape Optimization of a Reentry Body in Reacting Hypersonic Flow in Chemical Non-Equilibrium for Reducing both Drag and Heat Transfer

Ramesh K. Agarwal

Washington University in St. Louis, USA

3rd International Conference on Mechanical & Aerospace Engineering
San Francisco, 5-7 October 2015

Hypersonic Flow Characteristics

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Hypersonic flow characteristics differ from those at subsonic and even at supersonic speeds



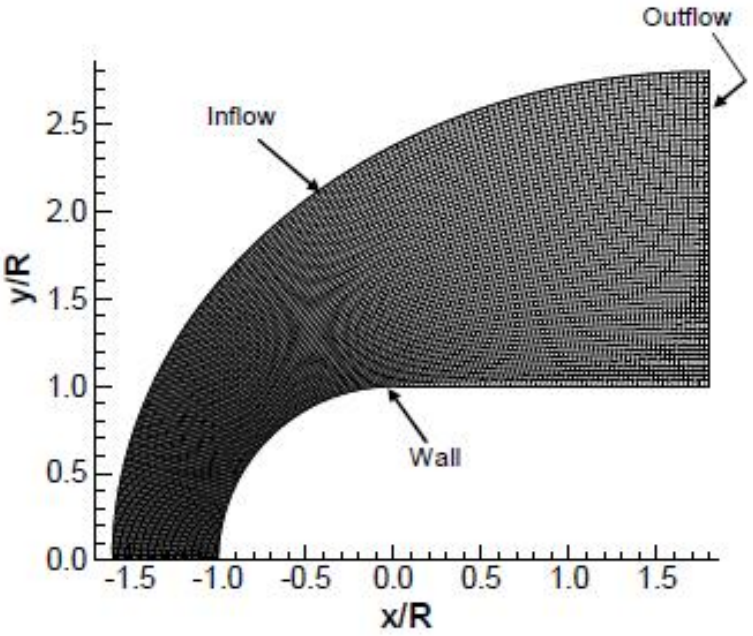
- Shockwave standoff distance decreases
- Shock and boundary layer interactions
- Transitional and Turbulent Flow
- Large drag coefficient
- High rates of heat transfer
- Molecular dissociation of air

Objectives

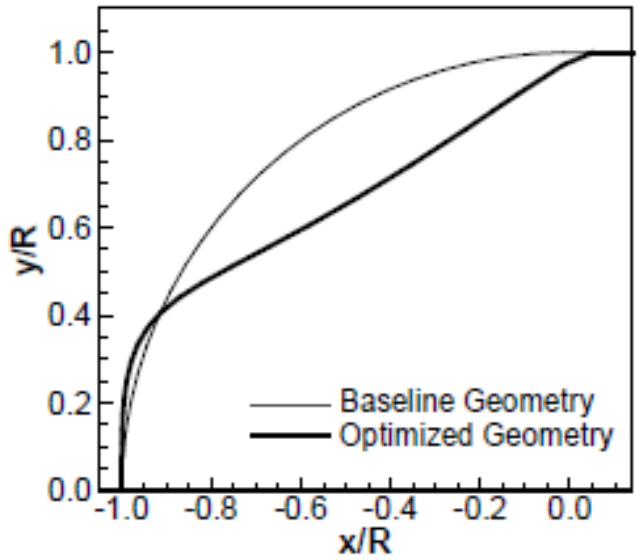
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- Simulate blunt body shapes in dissociating hypersonic flow
- Use a dual objective genetic algorithm to optimize a blunt body shape for minimizing both drag and heat transfer



Fine Grid (200x80 cells) around Lobb's Sphere



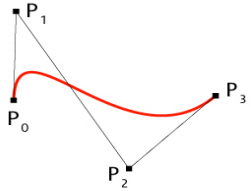
Baseline and Optimized Geometry
Mach number = 7.1

Computational Procedure

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I) Shape Generation



Bezier Curve

II) Mesh Generation

ICEM

III) CFD Simulation

ANSYS FLUENT

IV) Optimization

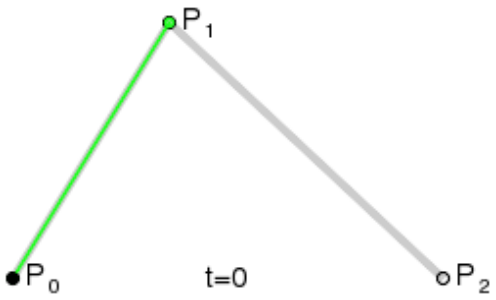
Genetic Algorithm

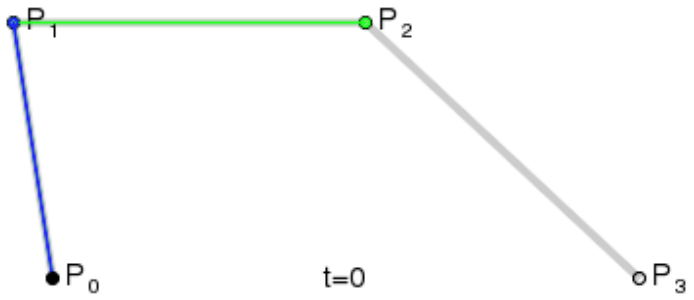
Shape Generation

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Bezier Curves





- Fix initial and end points
- Fix initial and final slope
- Control point information is
  - Easily stored
  - Easily swapped between curves
- Changes in control points result in similar changes to the curve

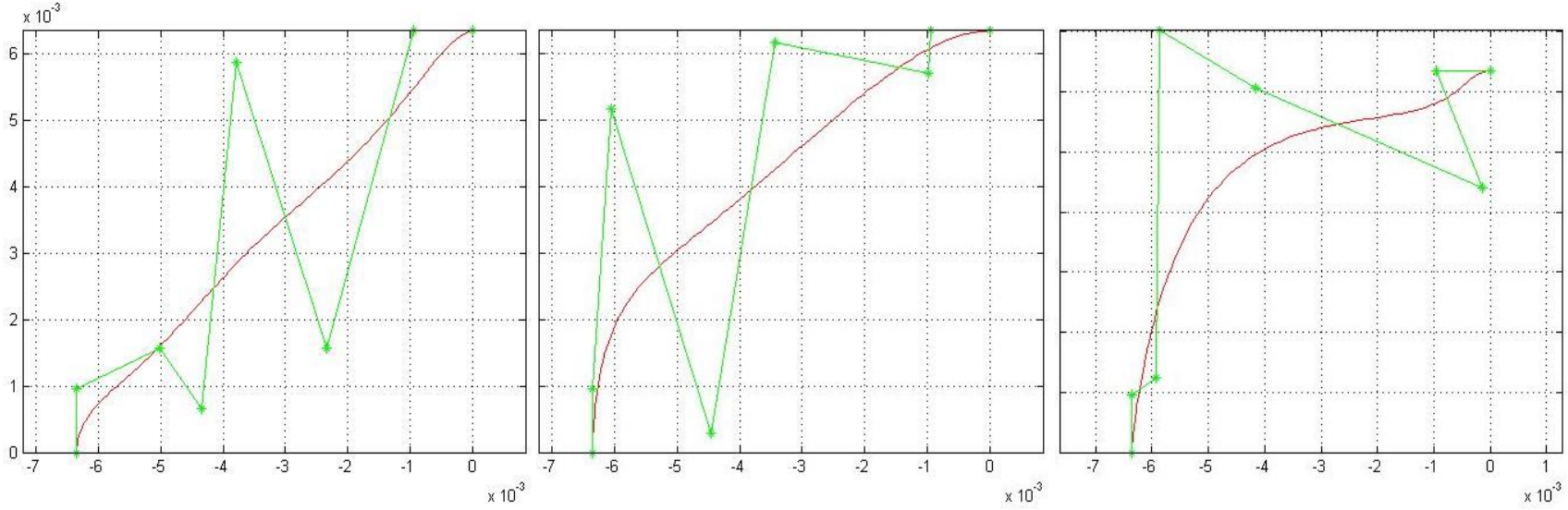
Shape Generation (contd.)

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Random Shapes -- Generated

- Fixed first two and final two control points
- Remaining four are randomly generated



Case 1 Case 2 Case 3

Mesh Generation

ICEM Meshing Software

- Automated via calling a script
  - Loads the shape profile (red curve)
  - Same mesh except for the shape profile portion
  - Segmented mesh most accurate and efficient

Mesh Study

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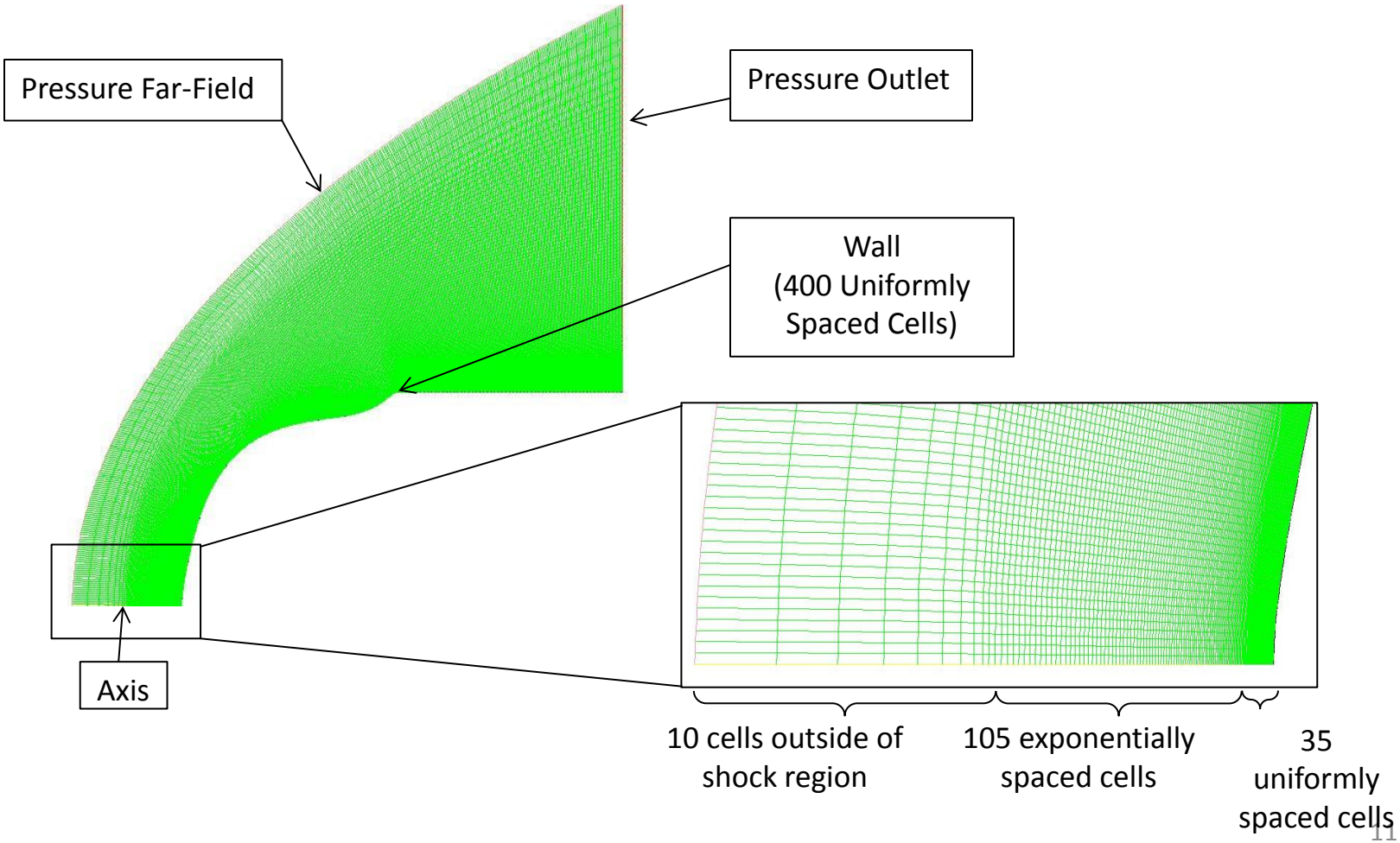
		Sphere		Random body shape		
Mesh type	Mesh size	C_D error	HT error	C_D error	HT error	Maximum $y+$
Reference	631×1250	— —	— —	— —	— —	0.87
Uniform	80×200	0.1	29.3	7.3	26.5	3.64
Uniform	120×200	0.1	18.6	5.5	18.9	2.88
Uniform	160×400	0.1	9.3	3.4	11	2.27
Uniform	200×400	0	8.8	2.8	10.6	2.14
Segmented	$(390\text{-}10) \times 400$	0	4.0	0.7	2.6	0.99
Segmented	$(85\text{-}115) \times 400$	0	8.3	1.5	6.5	0.85
Segmented	$(44\text{-}146\text{-}10) \times 400$	0	7.3	1.7	5.8	0.85
Segmented	$(25\text{-}75\text{-}10) \times 400$	0	8.3	2.7	11.7	1.00
Mesh of choice	$(35\text{-}105\text{-}10) \times 400$	0	7.5	2.2	5.8	0.76

Mesh Generation (contd.)

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Segmented Mesh

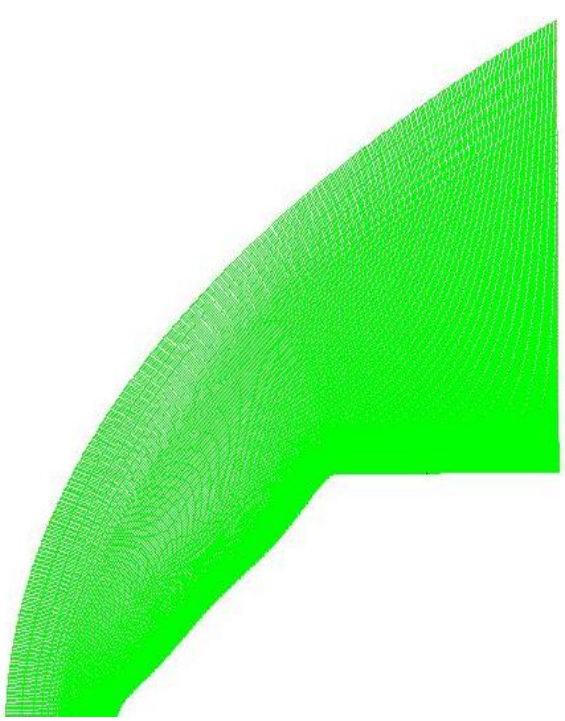


Mesh Generation (contd.)

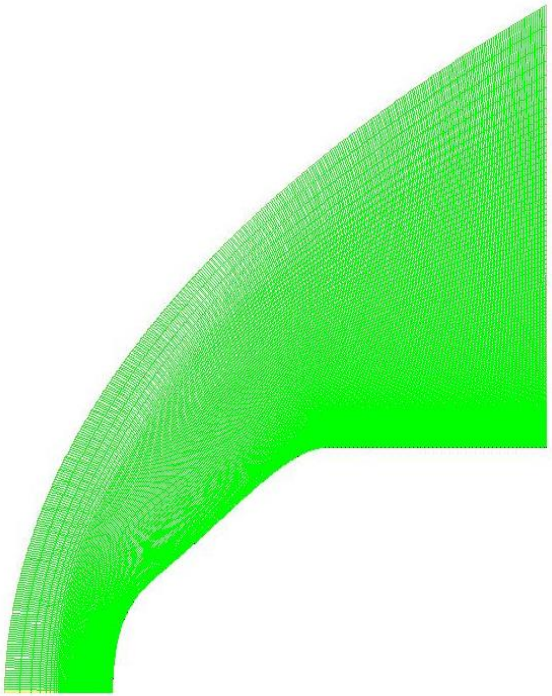
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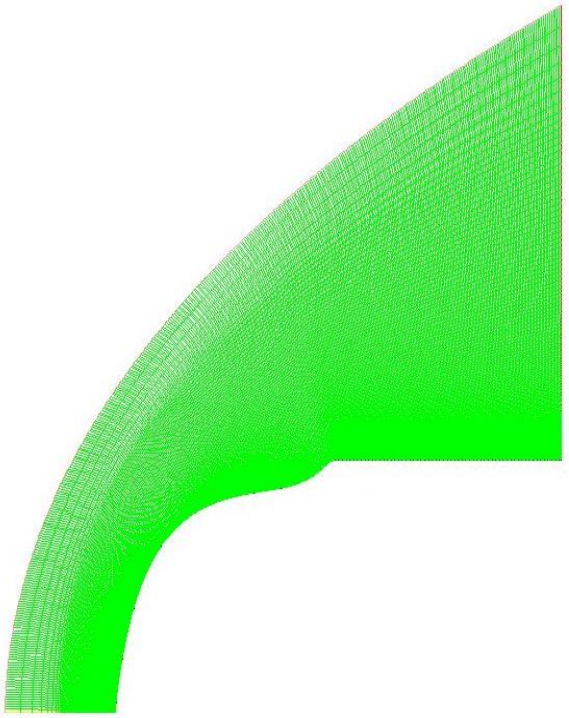
Random Shape Examples – Mesh Generation



Case 1



Case 2



Case 3

CFD Simulation

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ANSYS FLUENT

- Automated via calling a script
  - Loads the mesh
  - Solves for the flow field
    - Finds quantities such as pressure and skin friction coefficient, along with drag and maximum heat flux
  - Outputs design objectives (drag and maximum heat flux)

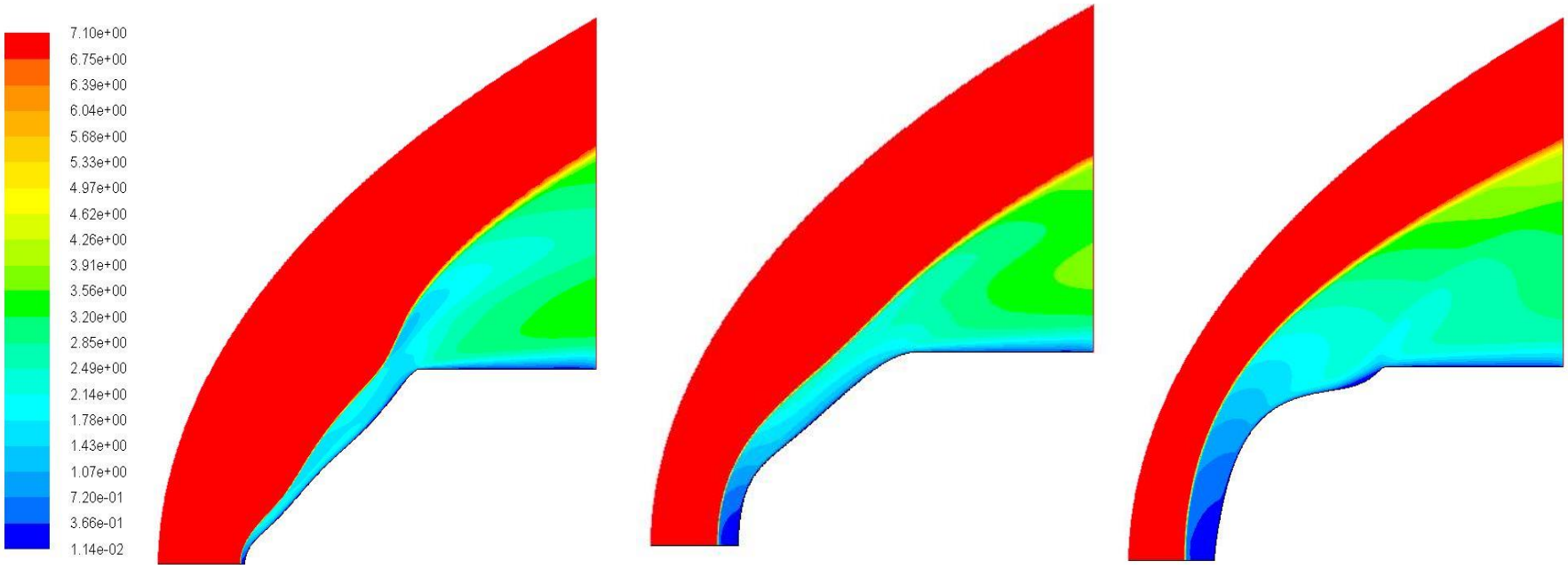
- Converged solution
  - Extremely important to ensure that solutions have converged
    - All residuals must be below 1E-4
    - Drag and heat flux must be converged to a steady state value
  - The simulation must be grid independent, accurate and efficient

CFD Simulation (contd.)

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Random Shape Examples -- Simulations
Mach Contours



Curve 1
High Drag
High Heat Transfer

Curve 2
Low Drag
Medium Heat Transfer

Curve 3
High Drag
Low Heat Transfer

Optimization

Genetic Algorithm (GA)

- Stochastic optimization algorithm inspired by biological evolution
  - Individual cases are iterated over, combining traits of the best individuals until convergence is achieved

- Generally employs the following steps:
  - Initialization
  - Evaluation
  - Natural Selection
  - Reproduction
  - Check for Convergence

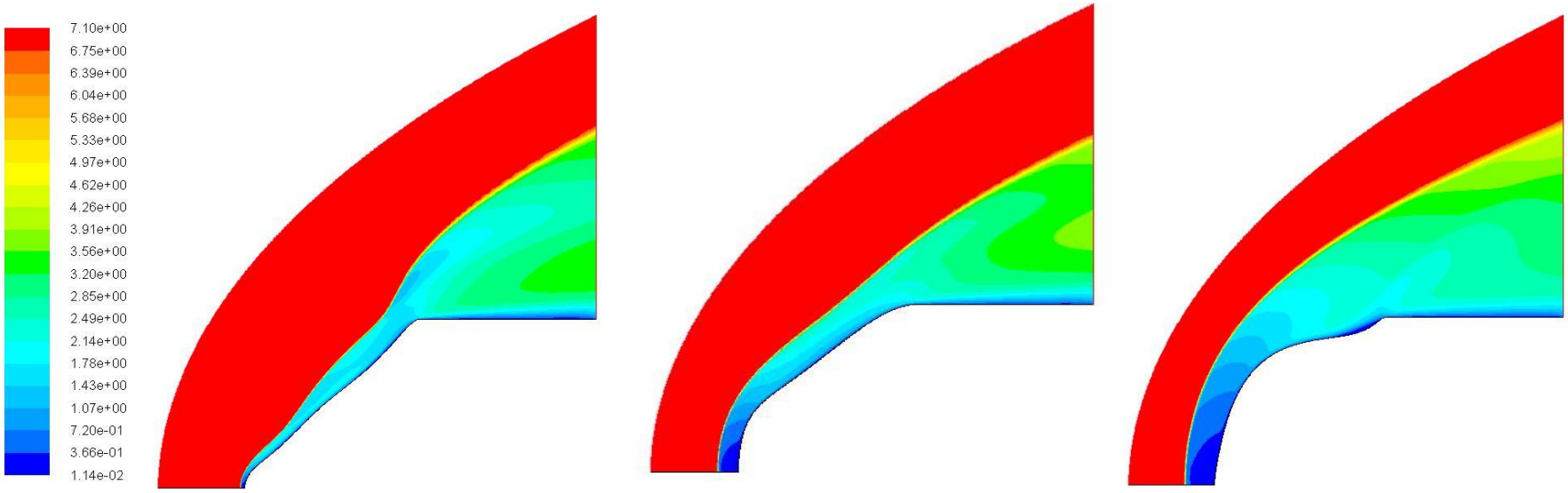
Genetic Algorithm

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Initialization

- Random generation of individuals (body shapes) is simulated



Curve 1
High Drag
High Heat Transfer

Curve 2
Low Drag
Medium Heat Transfer

Curve 3
High Drag
Low Heat Transfer

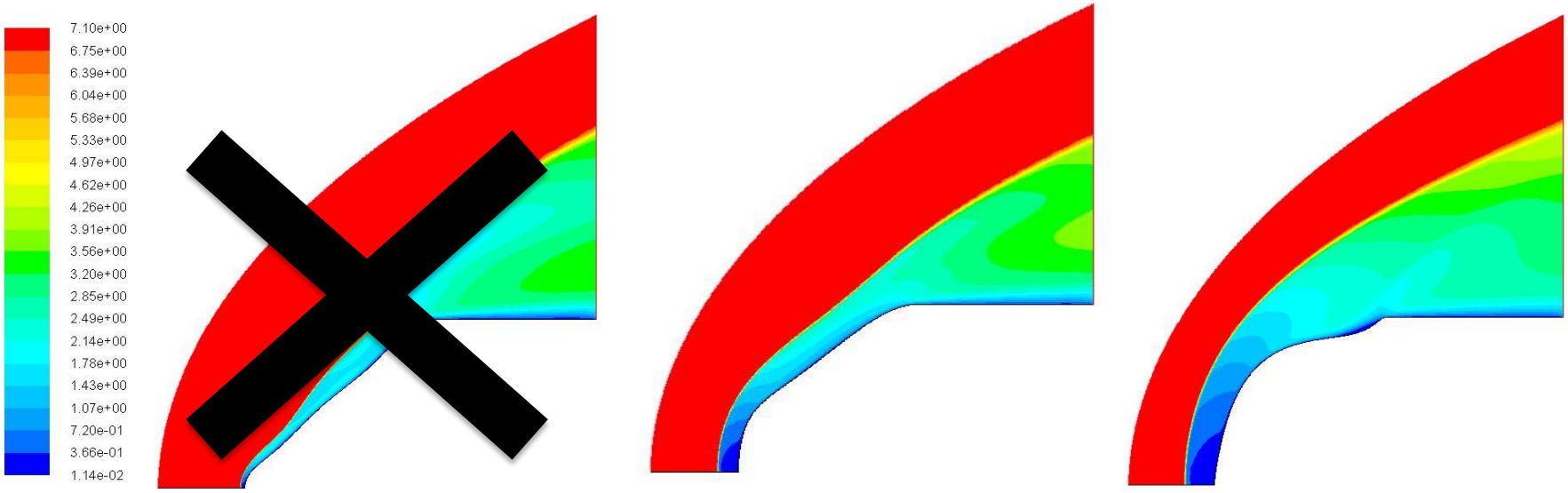
Genetic Algorithm (contd.)

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Evaluation and Natural Selection

- Objective values (drag and heat transfer) of each curve are compared
- Values are sorted from best to worst
- Worst half of the individuals are discarded



Curve 1
High Drag
High Heat Transfer

Curve 2
Low Drag
Medium Heat Transfer

Curve 3
High Drag
Low Heat Transfer

Genetic Algorithm (contd.)

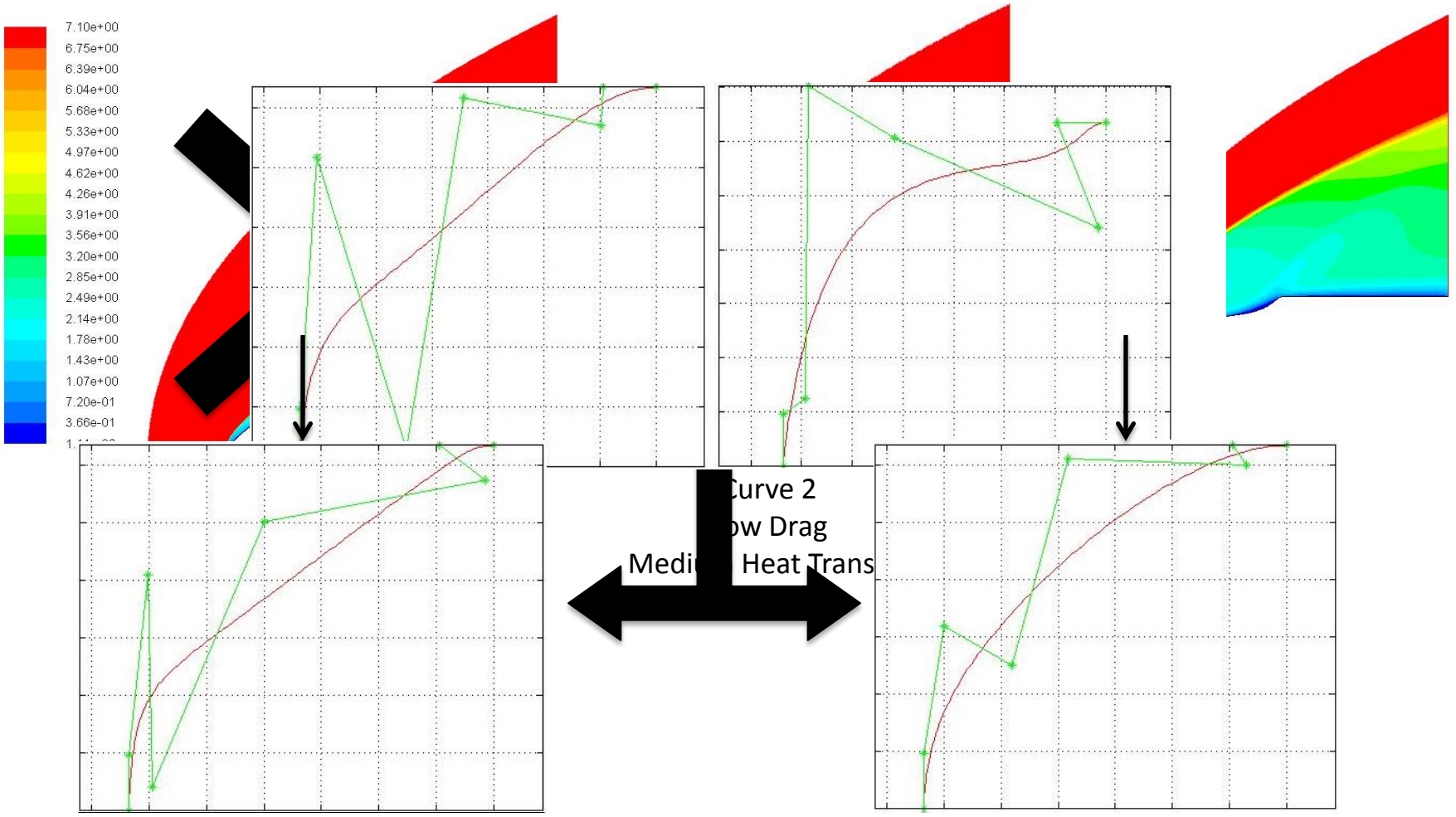
Reproduction

- Involves Parent Selection, Crossover, and Mutation
  - Parent selection
    - Pairs of parent shapes are selected using a skewed random draw
    - Higher fitness means higher probability of selection
  - Crossover
    - Paired curves randomly exchange Bezier point information
  - Mutation
    - Randomly selected Bezier points of randomly selected curves are randomly altered

Genetic Algorithm (contd.)

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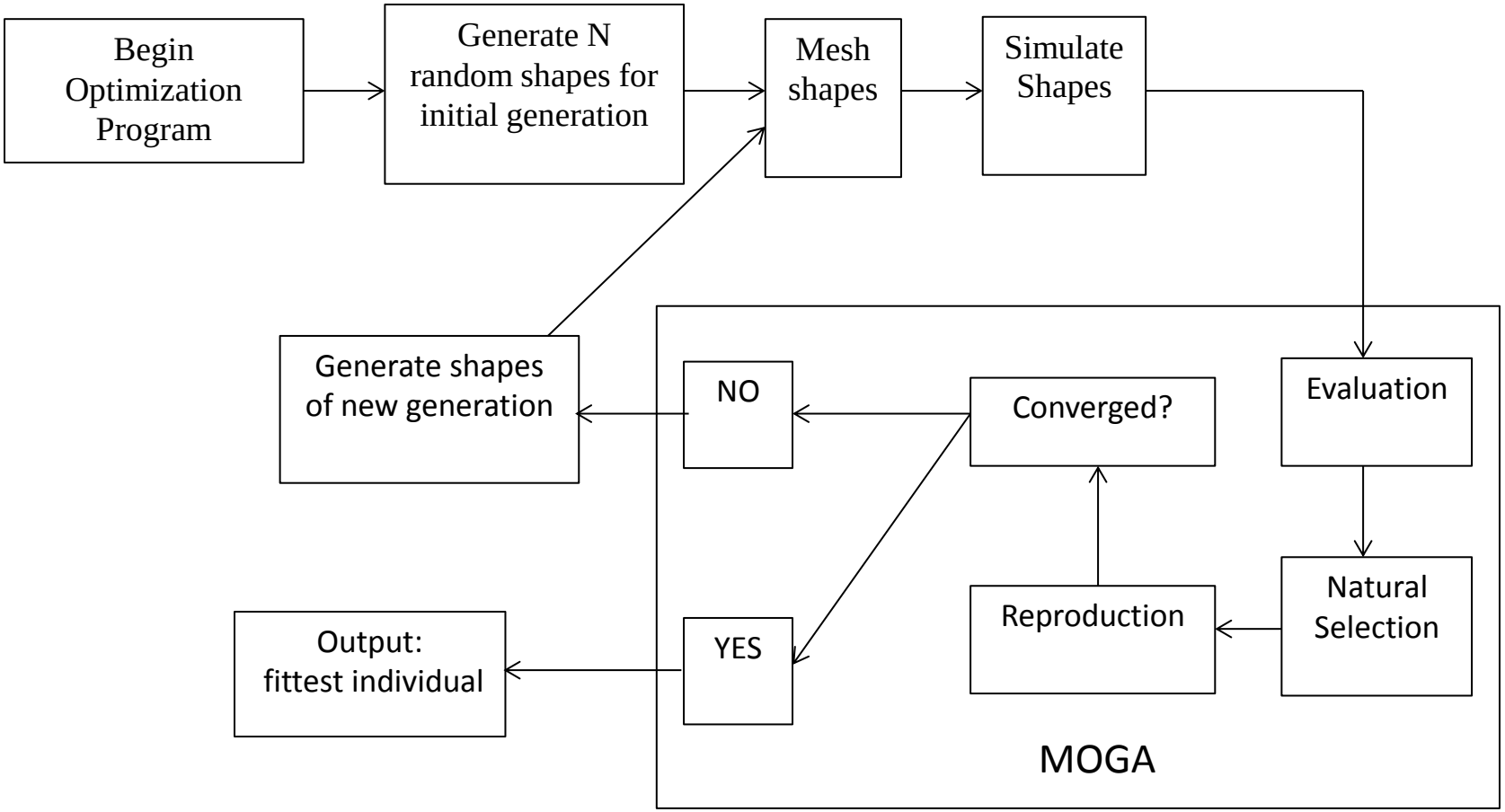
Genetic Algorithm (contd.)

Check for Convergence

- If convergence criteria is met, the fittest profile is output as the solution

- Criteria include
  - Similarity between individuals in the current generation
  - Similarity between current and previous generations
  - Number of generations simulated

Overview of Optimization



Results

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Weighted Objective Values

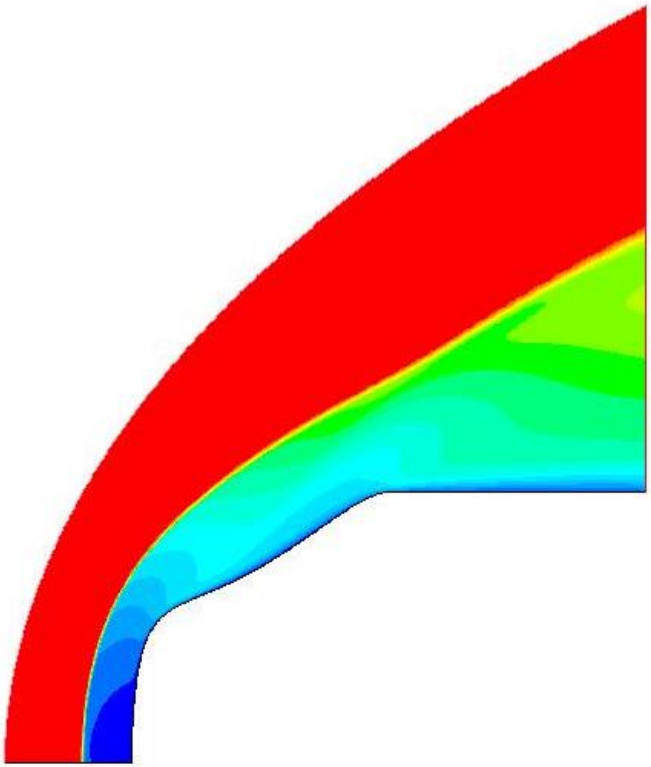
- Multi-objective optimization does not necessarily has a single solution
- Changes in importance of objective values gives different results
- Current cases considered
  - Evenly weighted drag and heat transfer
  - 0.75 drag vs. 1.0 heat transfer (HT) as relative weights
  - 0.5 drag vs. 1.0 HT as relative weights

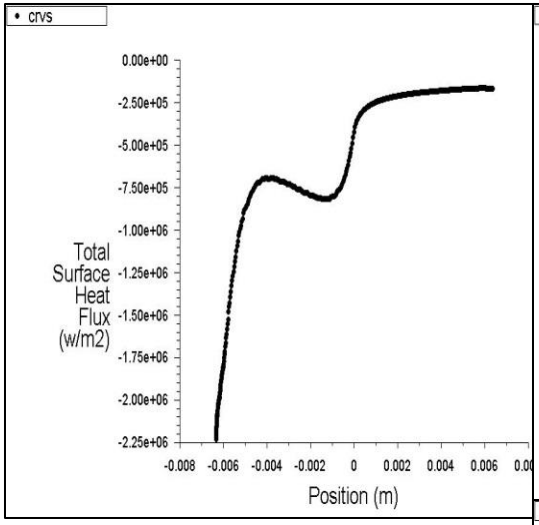
Results (contd.)

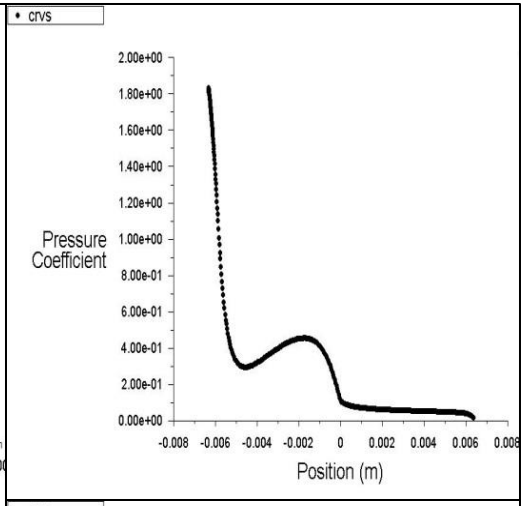
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Evenly Weighted Drag vs. HT

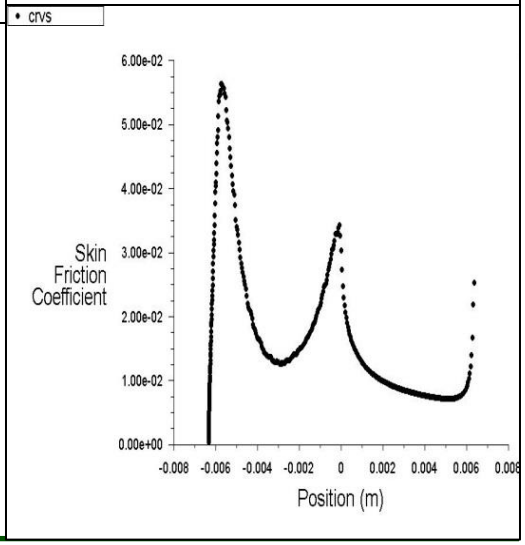






CD reduced by 22%

Max-HT reduced by 13%

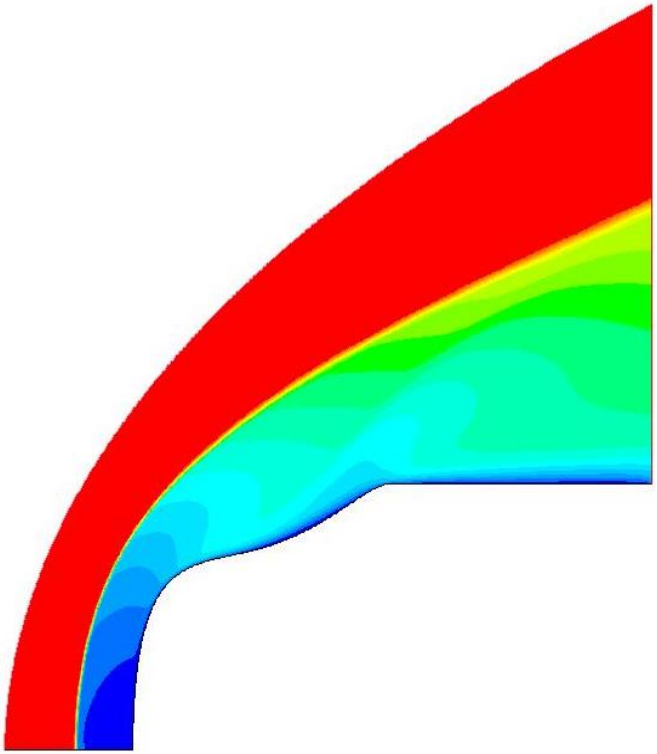


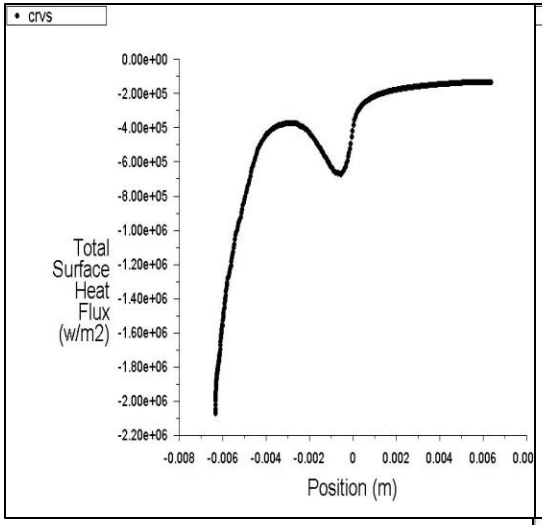
Results (contd.)

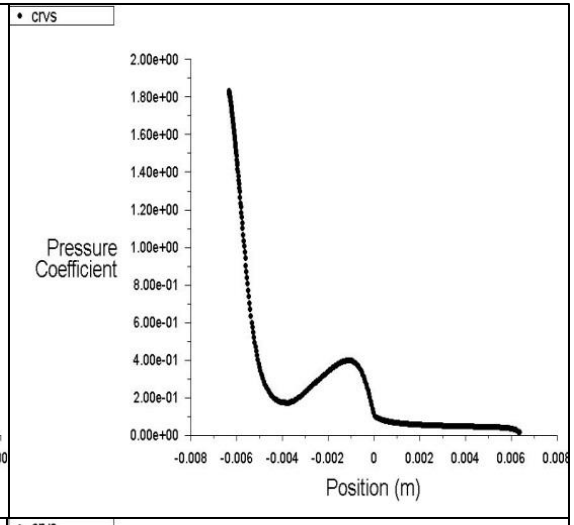
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0.75 vs. 1.0 weighted
Drag vs. Heat Flux

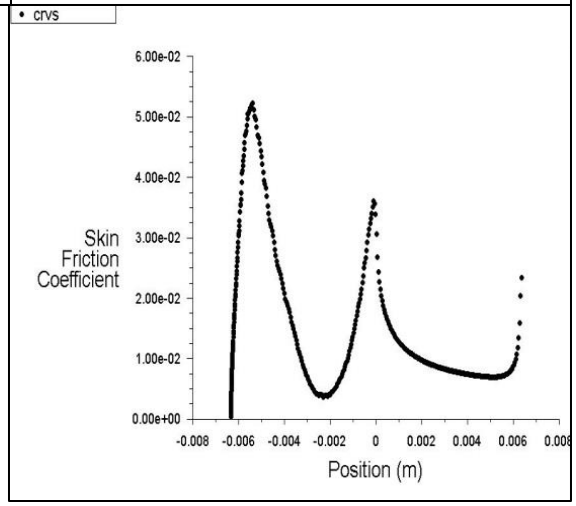






CD increased by 13%

Max-HT reduced by 19%

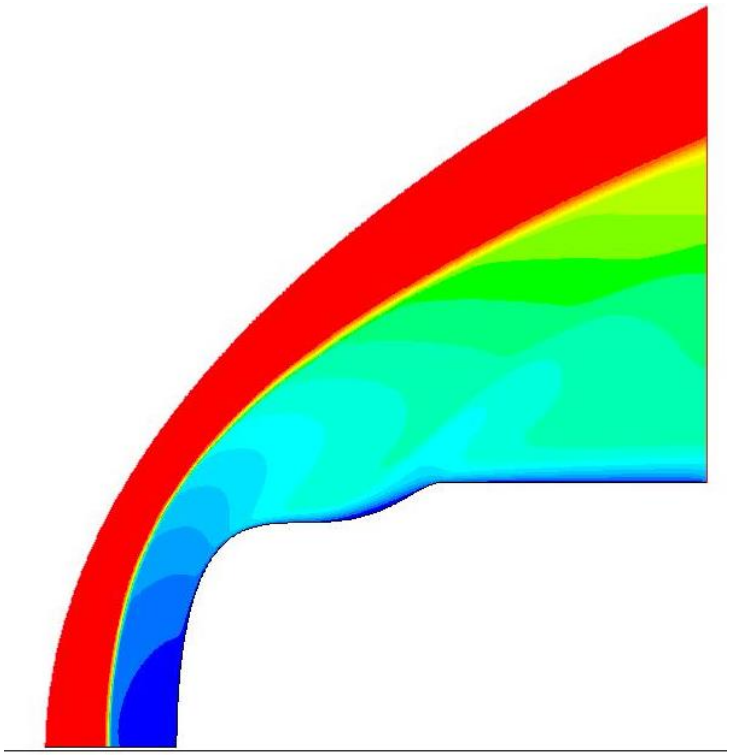


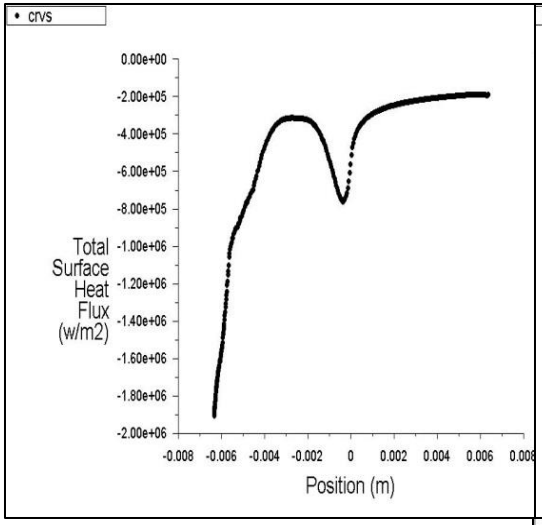
Results (contd.)

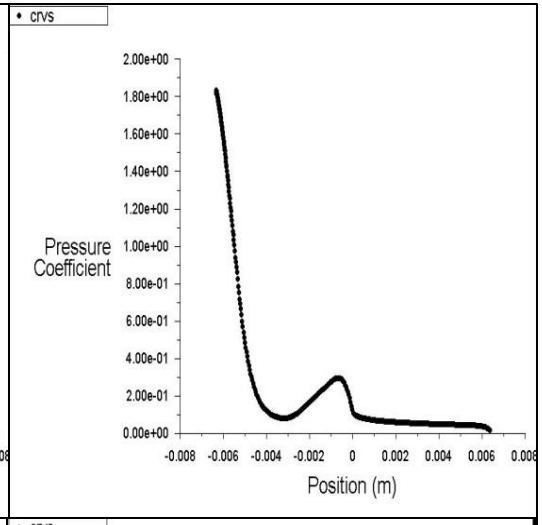
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0.5 vs. 1.0 weighted
Drag vs. Heat Flux

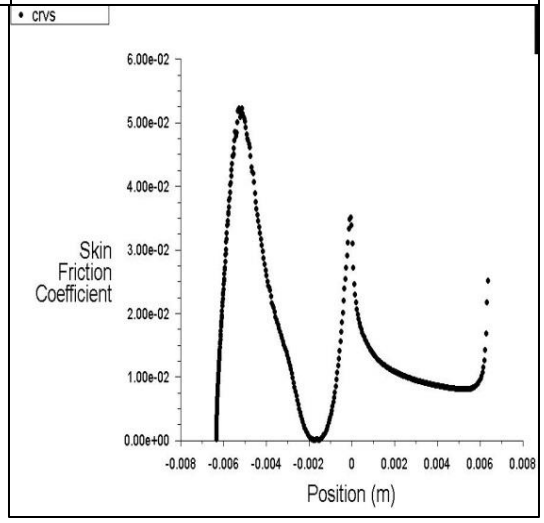






CD increased by 1%

Max-HT reduced by 26%

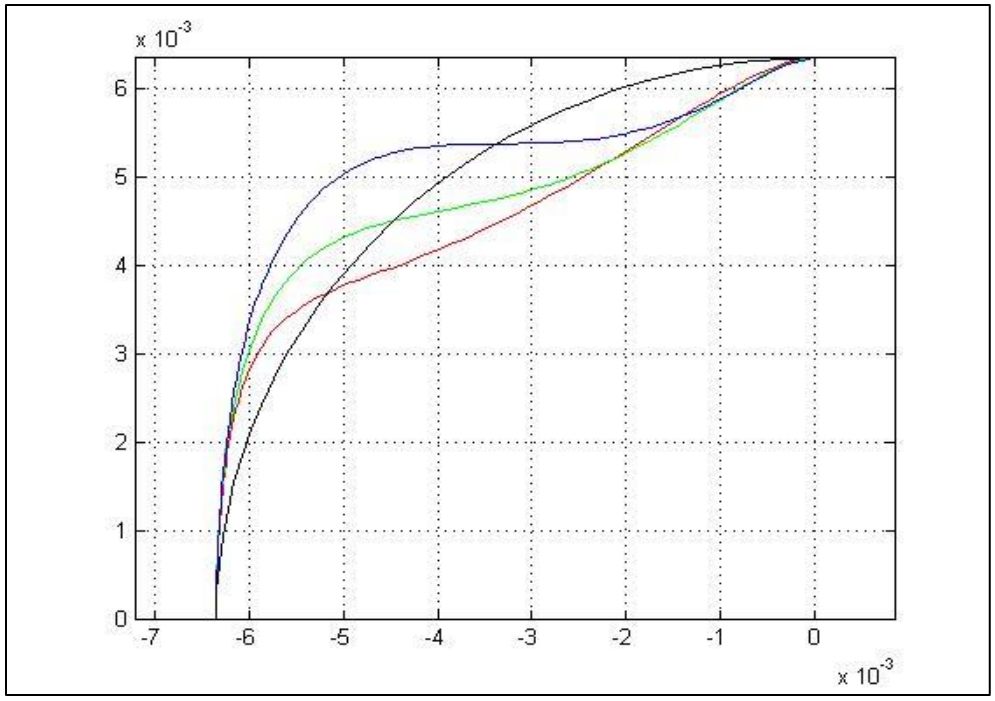


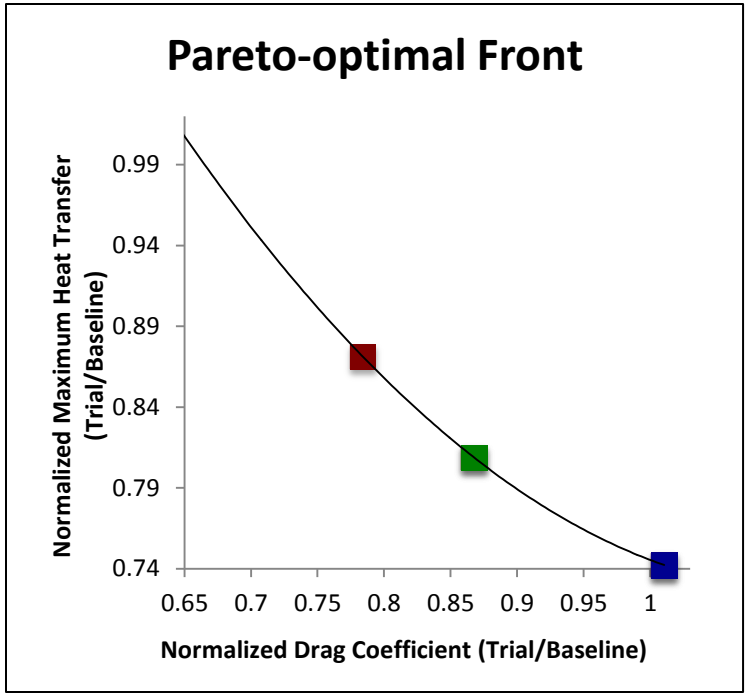
Results (contd.)

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Combined Results and Pareto-Optimal Front





Flow in Chemical Non-Equilibrium Results (DLR Case)

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Park's Five Species (C, O, O_2, CO, CO_2)Model

The Park'94 kinetic model contains 18 equations described in Table 1. The forward and reverse reaction rates for Arrhenius reactions are the following :

$K_f(T) = A_f T^{b_f} \exp(-E_f/T)$ [m^3 / (kmol . s)]

$K_r(T) = A_r T^{b_r} \exp(-E_r/T)$ [m^6 / ($kmol^2$. s)]

Table 1 shows the constants that were used to determine the reaction rates.

	Chemical Reaction	A_f	b_f	E_f	A_r	b_r	E_r
1	CO2+O2 ↔ CO+O+O2	6.90E18	-1.5	63275	1.14E11	-0.75	535
2	CO2+O ↔ CO+O+O	1.38E19	-1.5	63275	2.28E11	-0.75	535
3	CO2+C ↔ CO+O+C	1.38E19	-1.5	63275	2.28E11	-0.75	535
4	CO2+CO ↔ CO+CO+O	6.90E18	-1.5	63275	1.14E11	-0.75	535
5	CO2+CO2 ↔ CO+O+CO2	6.90E18	-1.5	63275	1.14E11	-0.75	535
6	CO+O2 ↔ C+O+O2	2.30E17	-1.0	129000	5.13E12	-1.00	0
7	CO+O ↔ C+O+O	3.40E17	-1.0	129000	7.59E12	-1.00	0
8	CO+C ↔ C+O+C	3.40E17	-1.0	129000	7.59E12	-1.00	0
9	CO+CO ↔ C+O+CO	2.30E17	-1.0	129000	5.13E12	-1.00	0
10	CO+CO2 ↔ C+O+CO2	2.30E17	-1.0	129000	5.13E12	-1.00	0
11	O2+C ↔ O+O+C	1.00E19	-1.5	59500	1.00E13	-1.00	0
12	O2+CO ↔ O+O+CO	2.00E18	-1.5	59500	2.00E12	-1.00	0
13	O2+CO2 ↔ O+O+CO2	2.00E18	-1.5	59500	2.00E12	-1.00	0
14	CO+CO ↔ CO2+C	2.33E06	0.5	65710	4.60E9	-0.25	0
15	CO+O ↔ O2+C	3.90E10	-0.18	69200	1.34E11	-0.43	0
16	CO2+O ↔ O2+CO	2.10E10	0.0	27800	4.11E7	0.50	23800
17	O2+O2 ↔ O+O+O2	2.00E18	-1.5	59500	2.00E12	-1.00	0
18	O2+O ↔ O+O+O	1.00E19	-1.5	59500	1.00E13	-1.00	0

http://www.esi-cfd.com/esi-users/fastran_kinetic_model

Flow in Chemical Non-Equilibrium Results (DLR Case)

CFD++ Six Species (C, C_2, O, O_2, CO, CO_2)Model

Number of Reaction	Reactants		Products
1	1.0 CO_2 + 1.0 CO_2	<->	1.0 CO + 1.0 O + 1.0 CO_2
2	1.0 CO_2 + 1.0 CO	<->	1.0 CO + 1.0 O + 1.0 CO
3	1.0 CO_2 + 1.0 O_2	<->	1.0 CO + 1.0 O + 1.0 O_2
4	1.0 CO_2 + 1.0 C	<->	1.0 CO + 1.0 O + 1.0 C
5	1.0 CO_2 + 1.0 O	<->	1.0 CO + 1.0 O + 1.0 O
6	1.0 CO + 1.0 CO_2	<->	1.0 C + 1.0 O + 1.0 CO_2
7	1.0 CO + 1.0 CO	<->	1.0 C + 1.0 O + 1.0 CO
8	1.0 CO + 1.0 O_2	<->	1.0 C + 1.0 O + 1.0 O_2
9	1.0 CO + 1.0 C	<->	1.0 C + 1.0 O + 1.0 C
10	1.0 CO + 1.0 O	<->	1.0 C + 1.0 O + 1.0 O
11	1.0 O_2 + 1.0 CO_2	<->	2.0 O + 1.0 CO_2
12	1.0 O_2 + 1.0 CO	<->	2.0 O + 1.0 CO
13	1.0 O_2 + 1.0 O_2	<->	2.0 O + 1.0 O_2
14	1.0 O_2 + 1.0 C	<->	2.0 O + 1.0 C
15	1.0 O_2 + 1.0 O	<->	2.0 O + 1.0 O
16	1.0 CO + 1.0 O	<->	1.0 C + 1.0 O_2
17	1.0 CO_2 + 1.0 O	<->	1.0 CO + 1.0 O_2
18	1.0 CO_2 + 1.0 C_2	<->	1.0 CO + 1.0 O + 1.0 C_2
19	1.0 C_2 + 1.0 CO_2	<->	1.0 C + 1.0 C + 1.0 CO_2
20	1.0 C_2 + 1.0 CO	<->	1.0 C + 1.0 C + 1.0 CO
21	1.0 C_2 + 1.0 C_2	<->	1.0 C + 1.0 C + 1.0 C_2
22	1.0 C_2 + 1.0 O_2	<->	1.0 C + 1.0 C + 1.0 O_2
23	1.0 C_2 + 1.0 C	<->	1.0 C + 1.0 C + 1.0 C
24	1.0 C_2 + 1.0 O	<->	1.0 C + 1.0 C + 1.0 O
25	1.0 CO + 1.0 C_2	<->	1.0 C + 1.0 O + 1.0 C_2
26	1.0 O_2 + 1.0 C_2	<->	1.0 O + 1.0 O + 1.0 C_2
27	1.0 CO + 1.0 C	<->	1.0 C_2 + 1.0 O

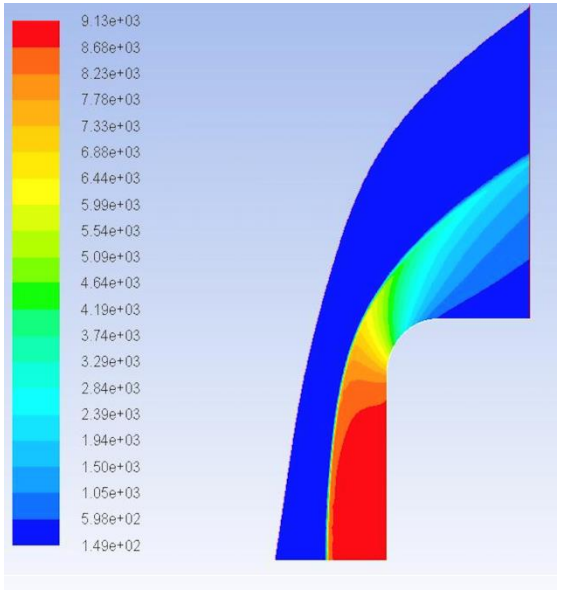
Flow in Chemical Non-Equilibrium Results (DLR Case)

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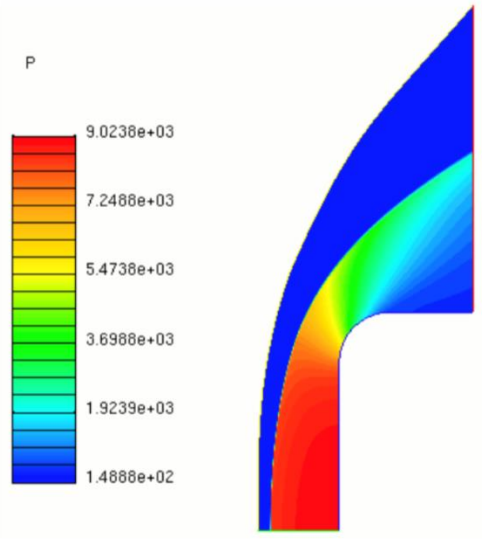
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Validation Case

- Experimental Data from the DLR case was used to validate the species model.
- The results showed that for the DLR case, the current chemical reaction model is not suitable. Pressure is calculated correctly, but not heat flux.
- Pressure contours are shown below



Fluent Pressure Contours



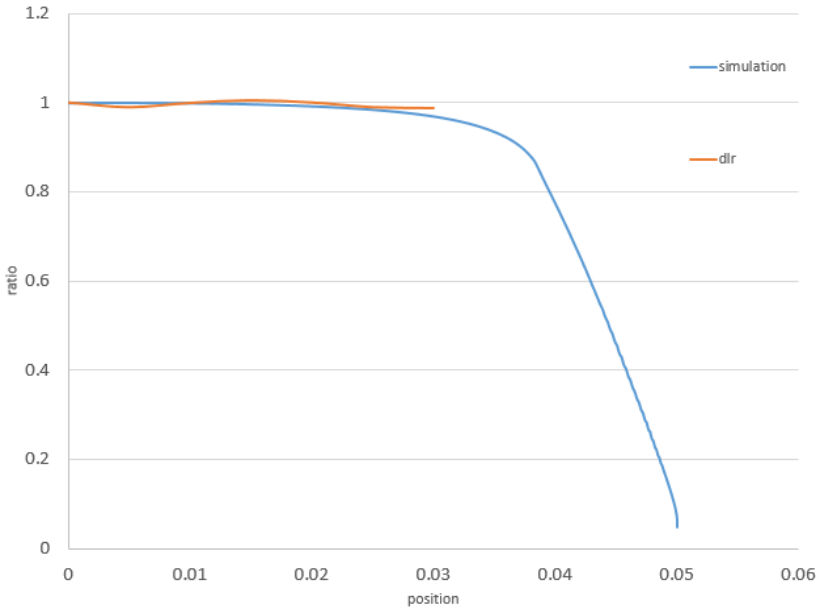
CFD++ Pressure Contours

Results (DLR Case)

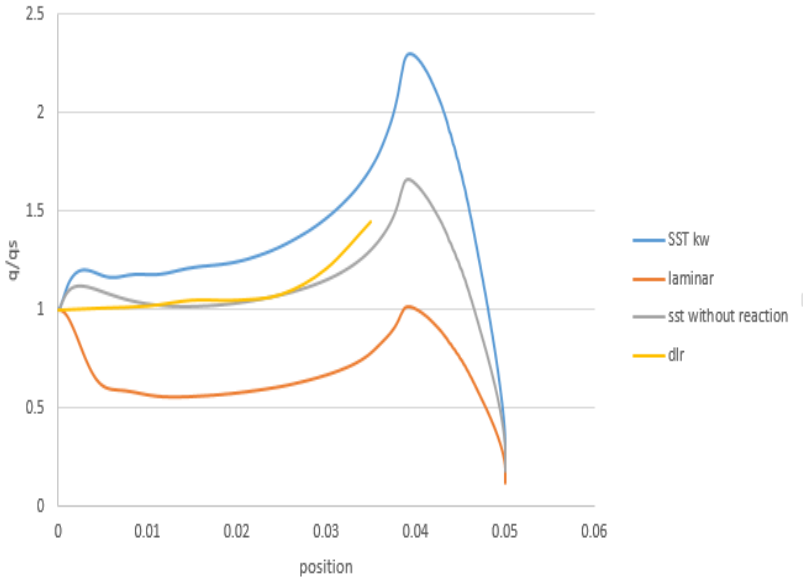
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Validation Case



Simulation vs. Experimental Pressure



Ratio of Heat Flux on the Body and Stagnation Point Heat Flux

Flow in Chemical Non-Equilibrium (Optimization Case)

Air Dissociation Five Species (N, N_2, NO, O, O_2)Model

$$O_2 + M \Leftrightarrow 2O + M$$

$$N_2 + M \Leftrightarrow 2N + M$$

$$NO + M \Leftrightarrow N + O + M$$

$$NO + O \Leftrightarrow O_2 + N$$

$$N_2 + O \Leftrightarrow NO + N$$

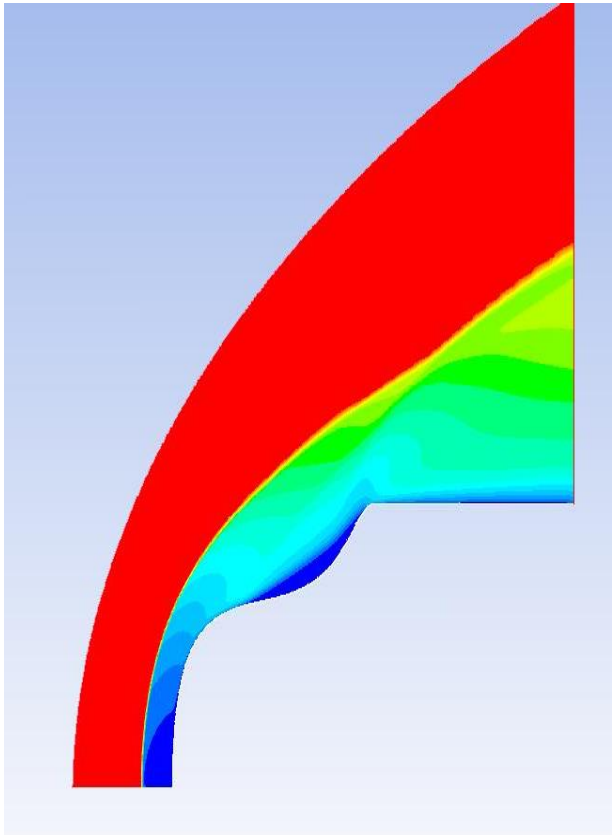
$$N + O \Leftrightarrow NO^+ + e^-$$

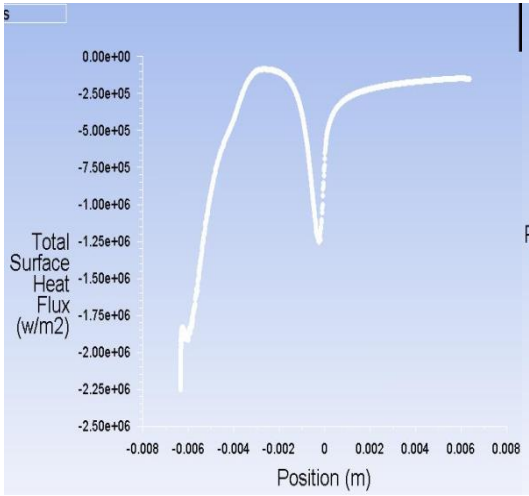
Results

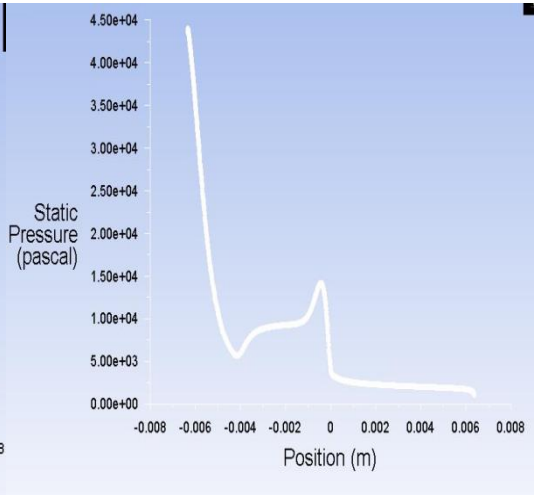
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Evenly weighted HT and Drag

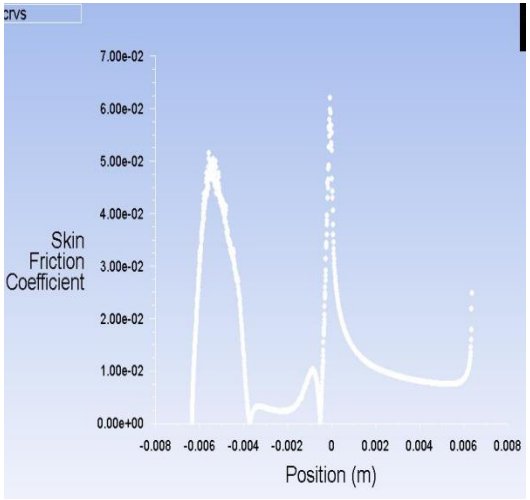






CD reduced by 14%

Max-HT reduced by 11%

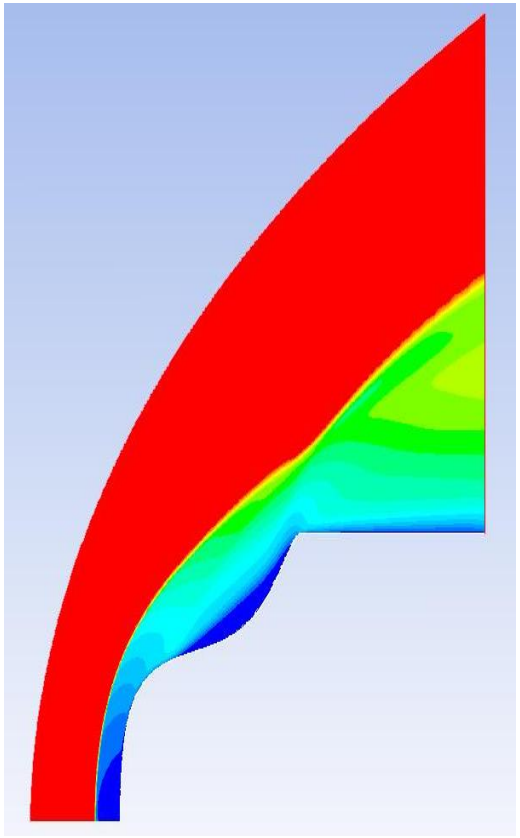


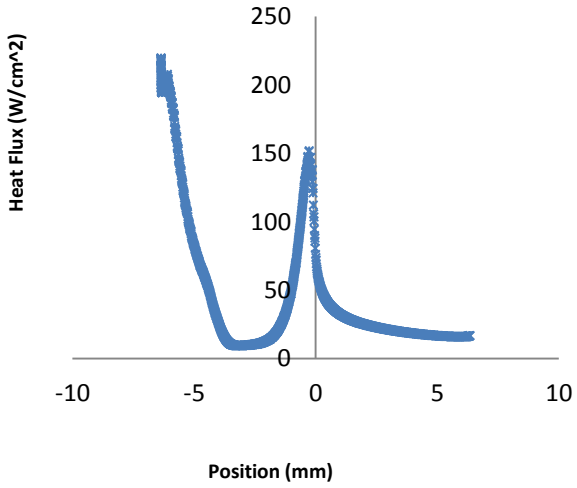
Results (contd.)

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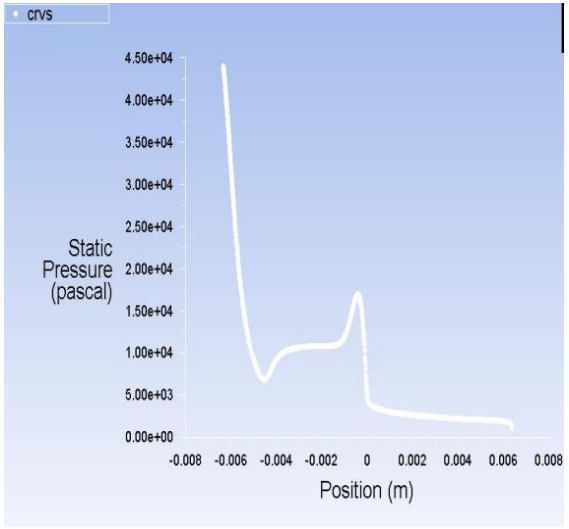
0.5 vs. 1.0 weighted
Heat Flux vs. Drag

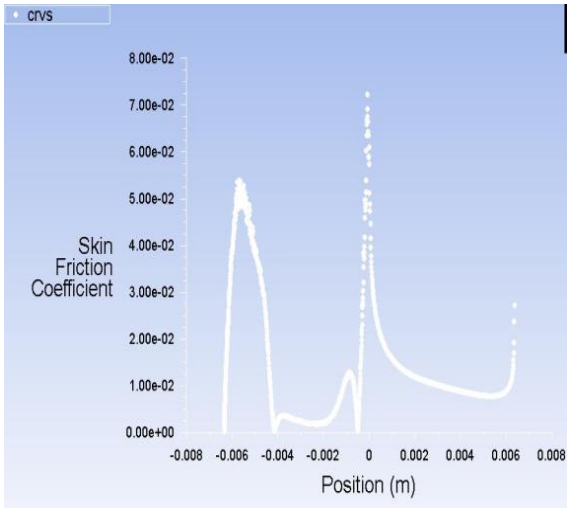




CD reduced by 16%

Max-HT reduced by 8%





Conclusions

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- Accomplishments
  - Successful simulation of blunt body shapes in dissociating hypersonic flow
  - Validation of CFD results against experimental data and other CFD code
  - Optimization of a blunt body shape for specified relative objectives of minimizing the drag and heat transfer

- Current Work
  - Simulations with more Bezier Points
  - Simulations at various Mach numbers
  - Simulations of 3D complex shapes

Thank you!

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