جامعة الإسكندرية
ALEXANDRIIA
UNIVERSITY
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FACULTY OF ENGINEERINIG

CONVECTIVE HEAT TRANSFER & AERODYNAMIC FORCES ON A MOVING TRUCK CARTAGE

Heat Transfer (MEC 311)

<u>Prepared for:</u> Prof.Dr. Wael El-Maghlany

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Power of Heat

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<u>Softwares Used:</u> ANSYS Workbench, ANSYS Discovery, ANSYS Mechanical, ANSYS Fluent, Excel and EES

DECEMBER 20, 2025

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Heat transfer course project

Case #1

A truck cartage that has a top surface of length (L) 8m and width (W) 2.5m, is travelling on the highway. The top surface of the cartage is subjected to 1000 W/m^2 solar radiation and the surface absorptivity is 20%. The ambient air is 20°C and the radiation from the cartage top surface is neglected (heat transferred from the surface is assumed to be only by convection to ambient air). **Using COMSOL, ANSYS or any other numerical software to find the following:**

(1) The effect of truck velocity from 20 to 140 km/h (use step of 20 km/h) on the local surface temperature (Plot T_s Vs. x for different velocities).

(2) The effect of truck velocity from 20 to 140 km/h (use step of 20 km/h) on the cartage top surface average temperature and overall convection coefficient (Plot $T_{s, avg}$ and h_{avg} Vs. U on the same graph).

(3) The effect of truck velocity from 20 to 140 km/h (use step of 20 km/h) on the friction force on the top surface and overall skin friction coefficient (Plot F_f and $C_{f, avg}$ Vs. U on the same graph).

(4) Compare the numerical results of (1), (2) and (3) with manual solution from empirical equations in your correlations book (you can use MATLAB, EES, EXCEL or calculate them manually).

Note:

- You must perform a mesh independence study using at least 3 mesh levels to select the suitable mesh for your simulation.

Instructions:

1. The project is performed in groups of 8 to 10 members.

3. A detailed report must be submitted containing the required results and graphs.

INTRODUCTION

Problem Description:

- Truck cartage roof $L = 8$ m, $W = 2.5$ m.
- Solar radiation = **1000 W/m²**, **absorptivity = 0.2**.
- Ambient air = **20°C**.
- Radiation from roof is **neglected** (only forced convection).
- Vehicle speeds from **20 – 140 km/h** in **20 km/h increments**.

Objectives:

1. Plot **local surface temperature vs. x** for different velocities.
2. Plot **average surface temperature** and **overall convection coefficient** vs. velocity.
3. Plot **friction force** and **average skin-friction coefficient** vs. velocity.
4. Compare **numerical results vs. empirical correlations**.
5. Evaluate how **vehicle speed** affects **cooling of the roof**.

Expected Physics:

- Forced convection over a flat plate.
- Boundary layer development.
- Heat balance on the roof.
- Skin friction role.

GEOMETRY CREATION

Truck Cartage Top Surface Model

- Geometry is sketched on ANSYS Discovery.
- It represents a 2D model of the roof (truck cartage top surface model) and the air boundary above it.
- Dimensions: 8 m (flat plate length) × 9 m (height of the Boundary).
- A 9 m height was chosen to avoid blockage effects and ensure sufficient free-stream region.
- Although the simulation is performed in 2D, the reported heat transfer and force quantities are scaled using the actual plate width (2.5 m) to represent the real truck roof.

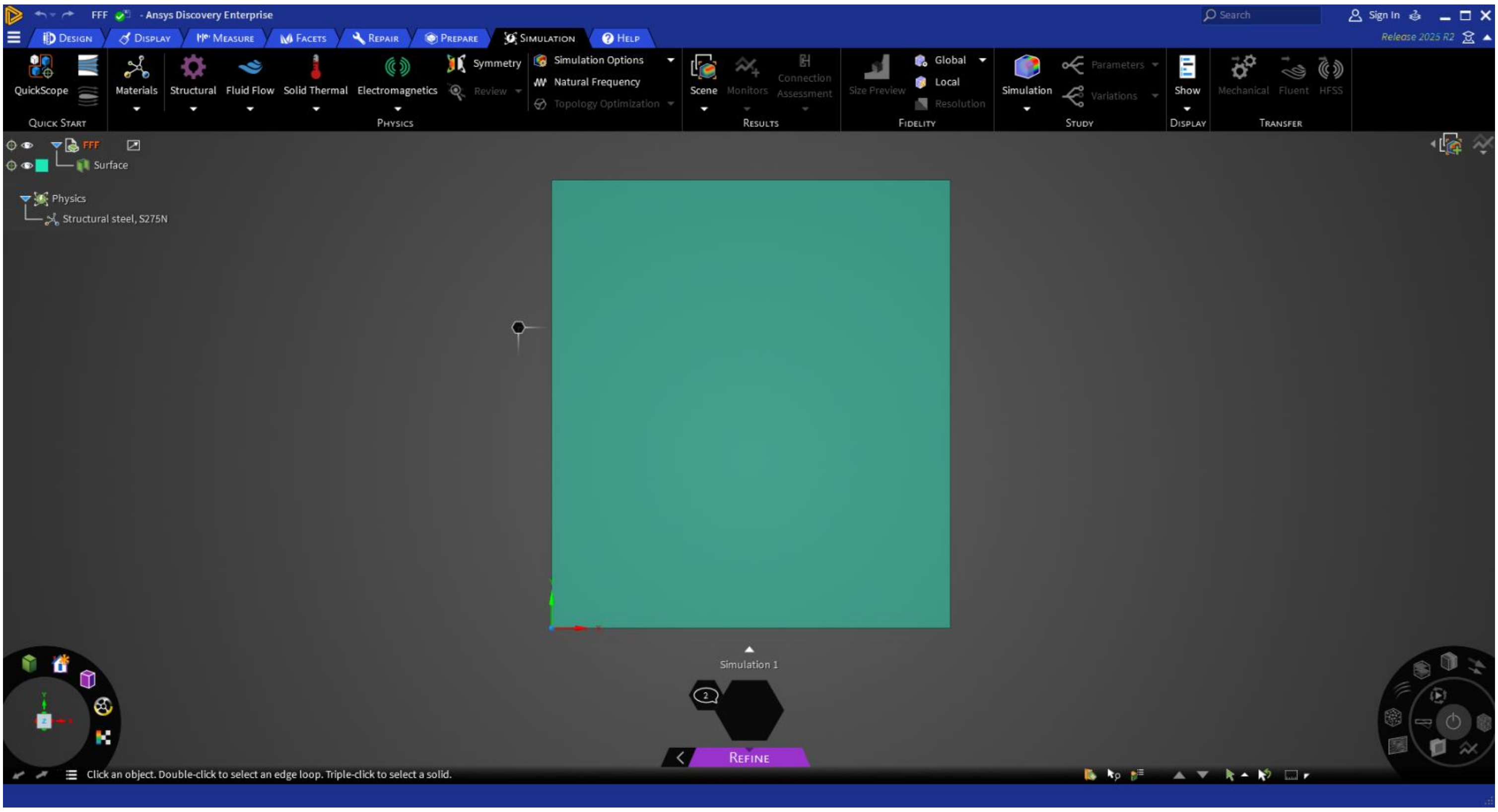

Figure 1: Geometry (ANSYS Discovery)

MESHING

- Three Mesh Phases for the mesh independence study.
- Disclaimer: We couldn’t provide any smaller global element size due to hardware limitations.

Coarse Mesh (Element Size: 0.10 m):

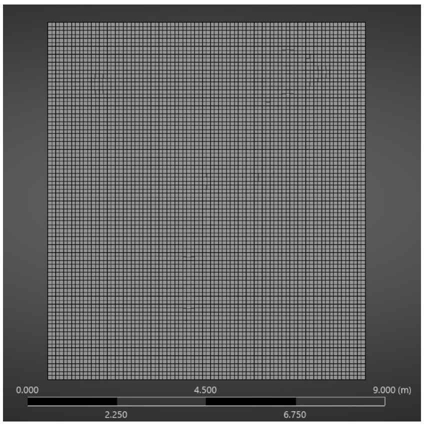

Figure 2.1: Mesh *(ANSYS Mechanical)*

Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Size	0.1 m
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Quality	
Inflation	
Advanced	
Automatic Methods	
Sheet Body Method	Quad Dominant
Sweepable Body Method	Sweep
Statistics	

Figure 2.2: Mesh Details *(ANSYS Mechanical)*

Details of "Body Sizing" - Sizing

Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Suppressed	No
Type	Element Size
Element Size	0.1 m
Advanced	
Defeature Size	Default (5.e-004 m)
Growth Rate	Default (1.2)
Capture Curvature	Yes
Curvature Normal Angle	Default (18.0°)
Local Min Size	Default (1.e-003 m)
Capture Proximity	No

Figure 2.3: Body Sizing Details *(ANSYS Mechanical)*

Medium Mesh (Element Size: 0.05 m):

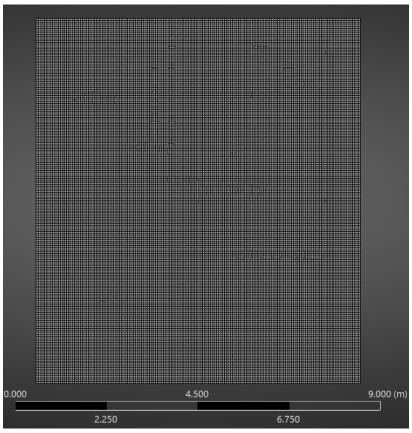

Figure 3.1: Mesh *(ANSYS Mechanical)*

Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Size	5.e-002 m
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Quality	
Inflation	
Advanced	
Automatic Methods	
Sheet Body Method	Quad Dominant
Sweepable Body Method	Sweep
Statistics	

Figure 3.2: Mesh Details *(ANSYS Mechanical)*

Details of "Body Sizing" - Sizing

Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Suppressed	No
Type	Element Size
Element Size	5.e-002 m
Advanced	
Defeature Size	Default (2.5e-004 m)
Growth Rate	Default (1.2)
Capture Curvature	Yes
Curvature Normal Angle	Default (18.0°)
Local Min Size	Default (5.e-004 m)
Capture Proximity	No

Figure 3.3: Body Sizing Details *(ANSYS Mechanical)*

Fine Mesh (Element Size: 0.02 m):

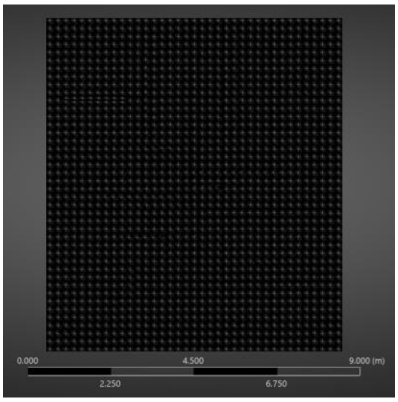

Figure 4.1: Mesh *(ANSYS Mechanical)*

Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Size	2.e-002 m
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Quality	
Inflation	
Advanced	
Automatic Methods	
Sheet Body Method	Quad Dominant
Sweepable Body Method	Sweep
Statistics	

Figure 4.2: Mesh Details *(ANSYS Mechanical)*

Details of "Body Sizing" - Sizing

Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Suppressed	No
Type	Element Size
Element Size	Default (2.e-002 m)
Advanced	
Defeature Size	Default (1.e-004 m)
Growth Rate	Default (1.2)
Capture Curvature	Yes
Curvature Normal Angle	Default (18.0°)
Local Min Size	Default (2.e-004 m)
Capture Proximity	No

Figure 4.3: Body Sizing Details *(ANSYS Mechanical)*

PHYSICS SETUP

General Settings:

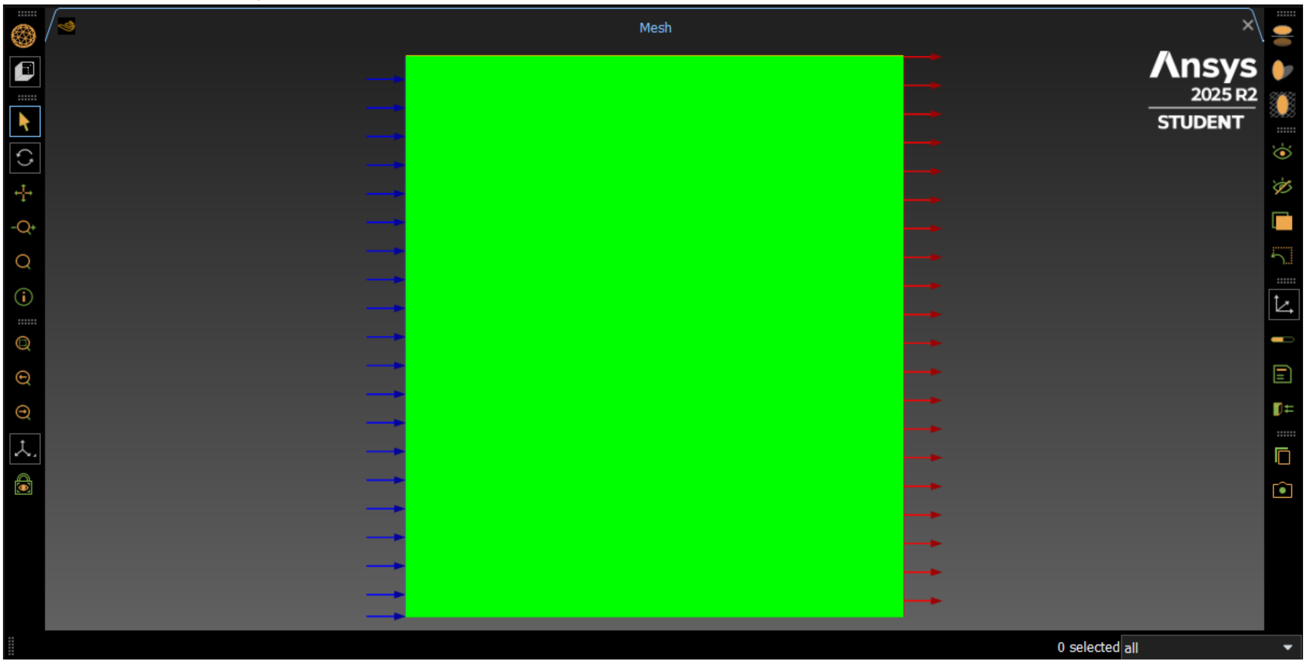

Figure 5: Meshing (ANSYS Fluent)

- The k–ω SST turbulence model was used due to its accuracy in near-wall boundary-layer resolution for external flows

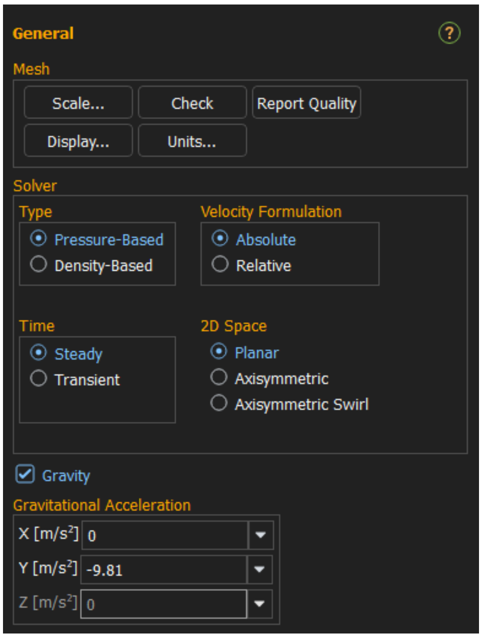

Figure 6: General (ANSYS Fluent)

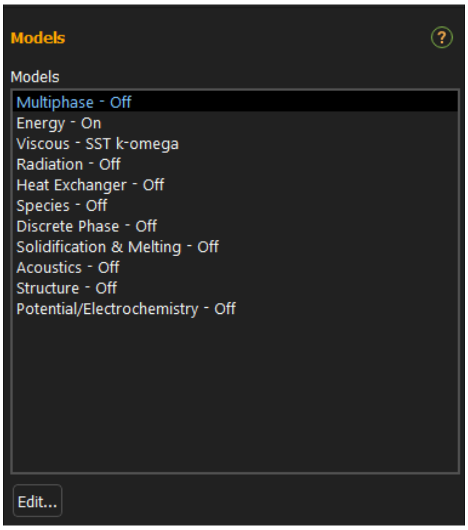

Figure 7: Models (ANSYS Fluent)

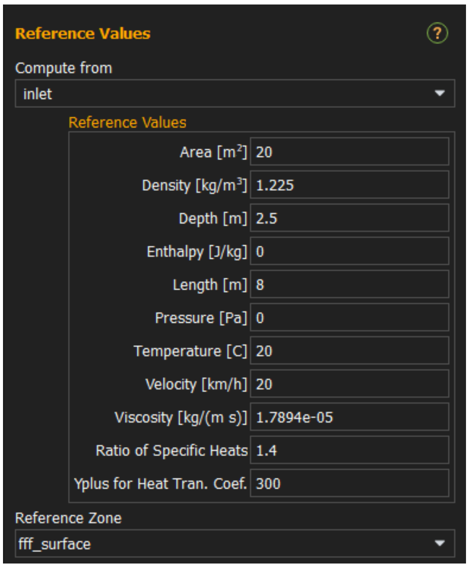

Figure 8: Reference Values (ANSYS Fluent)

Material Properties:

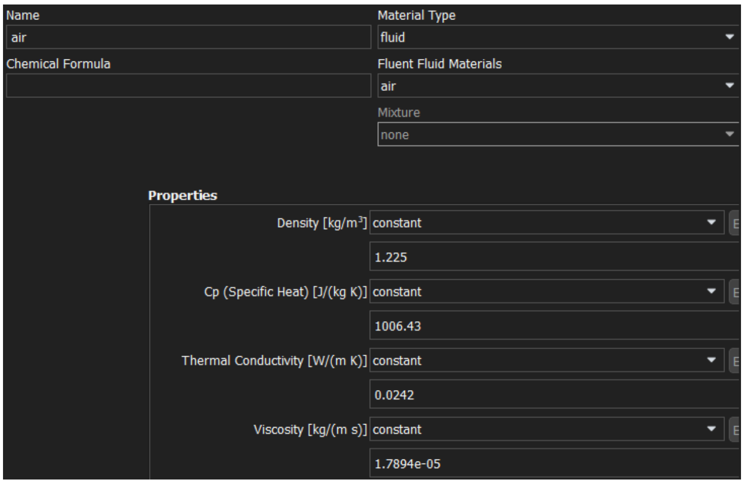

Figure 9.1: Air *(ANSYS Fluent)*

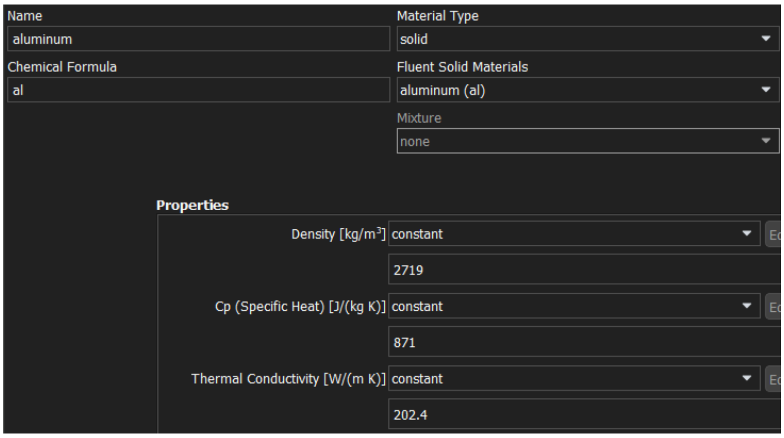

Figure 9.2: Aluminum *(ANSYS Fluent)*

Boundary Conditions:

i. Inlet:

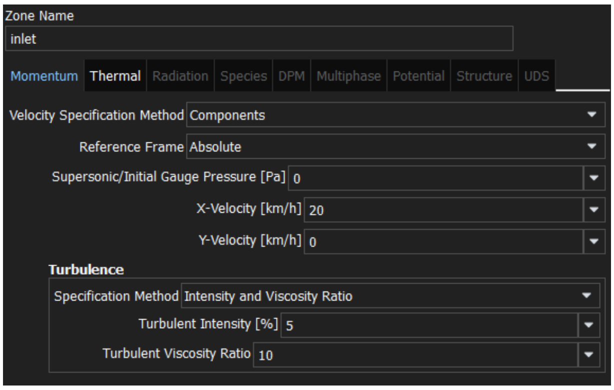

Figure 10.1: Inlet (Momentum) *(ANSYS Fluent)*

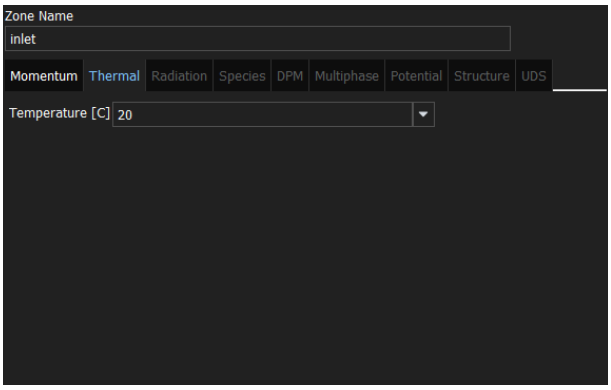

Figure 10.2: Inlet (Thermal) *(ANSYS Fluent)*

ii. Truck Cartage Plate:

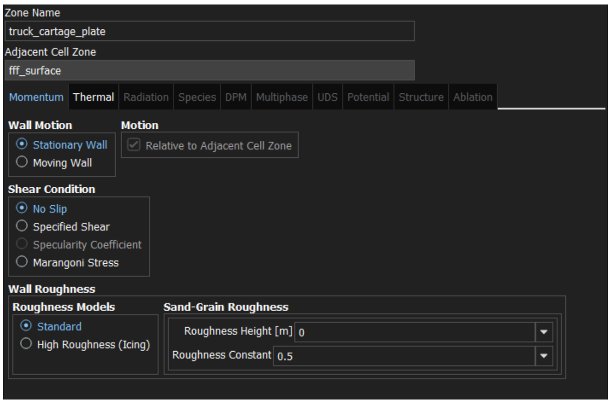

Figure 11.1: Plate (Momentum) *(ANSYS Fluent)*

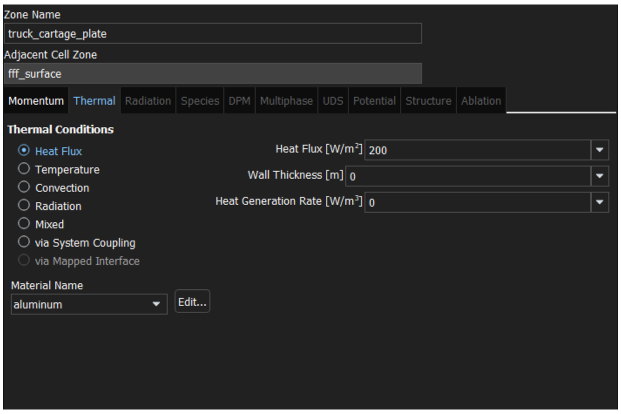

Figure 11.2: Plate (Thermal) *(ANSYS Fluent)*

iii. Outlet:

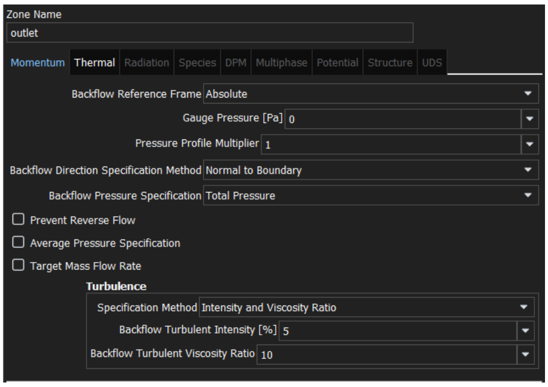

Figure 12.1: Outlet (Momentum) *(ANSYS Fluent)*

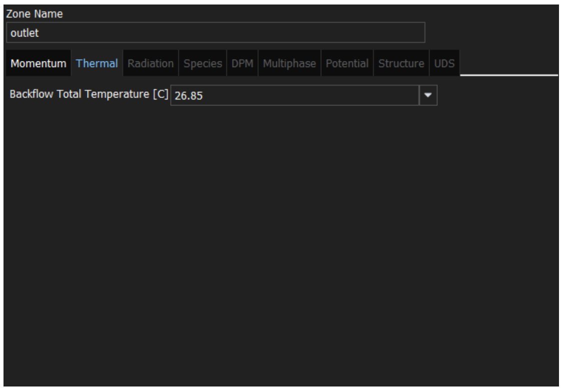

Figure 12.2: Outlet (Thermal) *(ANSYS Fluent)*

Report Definitions:

- We created multiple iso-surfaces along the x-axis to interpret the local Temperature on plate.

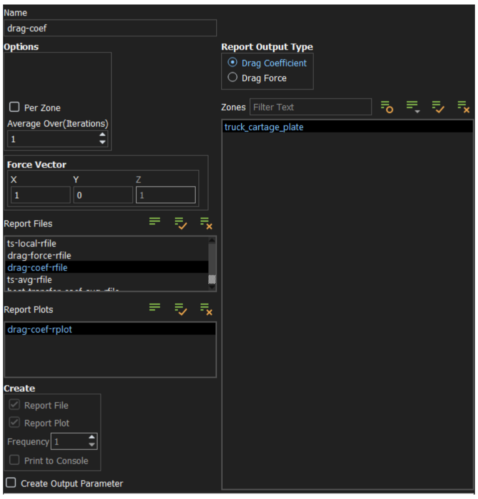

Figure 13.1: Drag Coefficient *(ANSYS Fluent)*

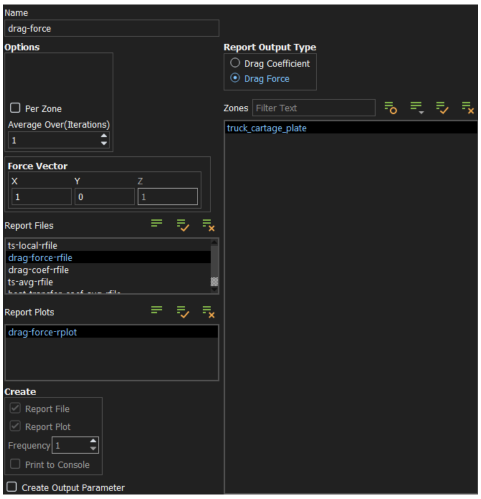

Figure 13.2: Drag Force *(ANSYS Fluent)*

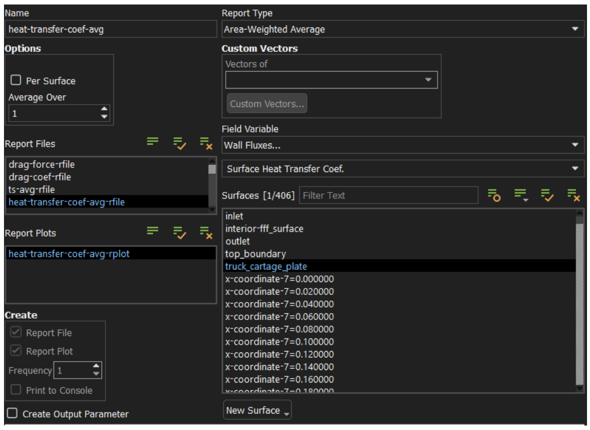

Figure 13.3: Average Heat Transfer Coefficient *(ANSYS Fluent)*

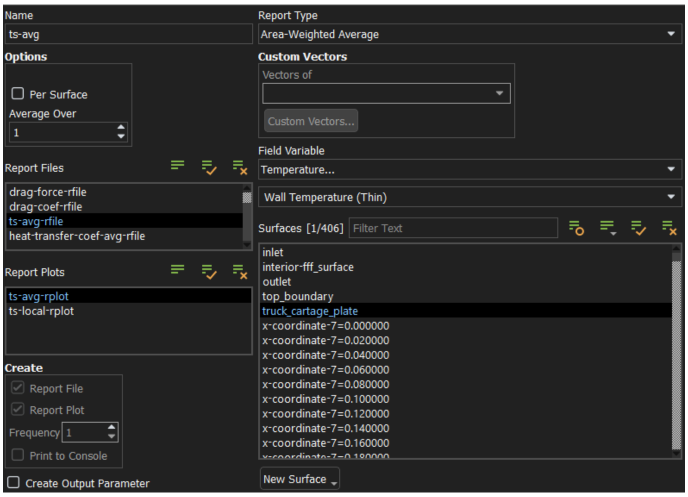

Figure 13.4: Average Temperature *(ANSYS Fluent)*

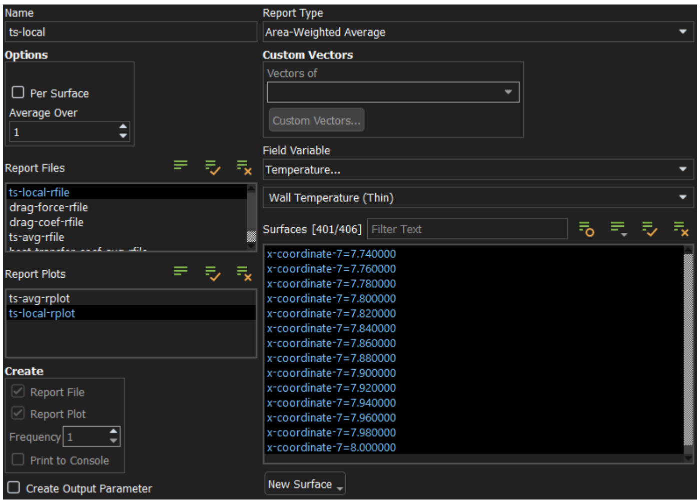

Figure 13.5: Local Temperature *(ANSYS Fluent)*

Calculation Settings:

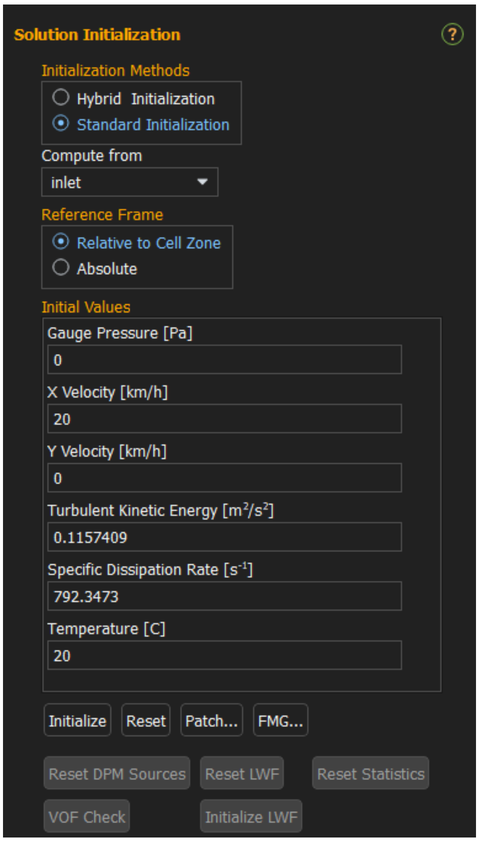

Figure 14.1: Initialization (ANSYS Fluent)

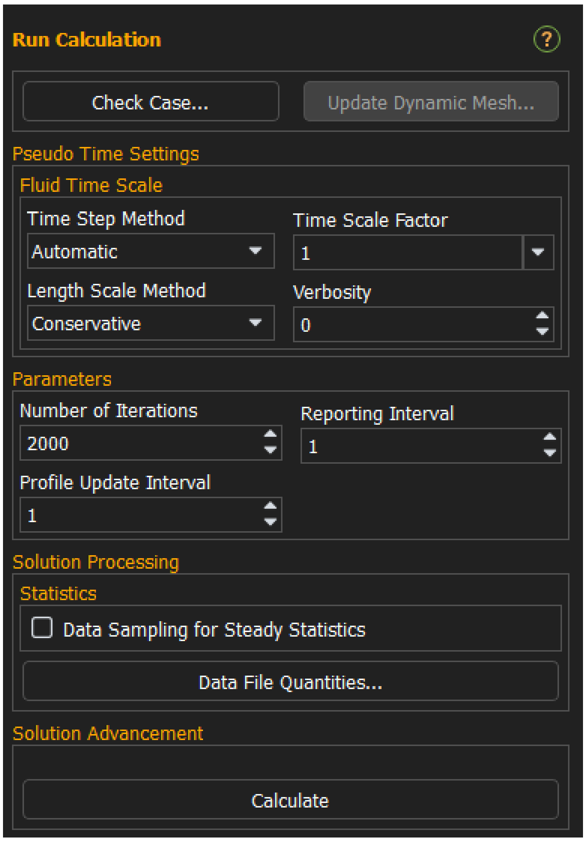

Figure 14.2: Run Calculation (ANSYS Fluent)

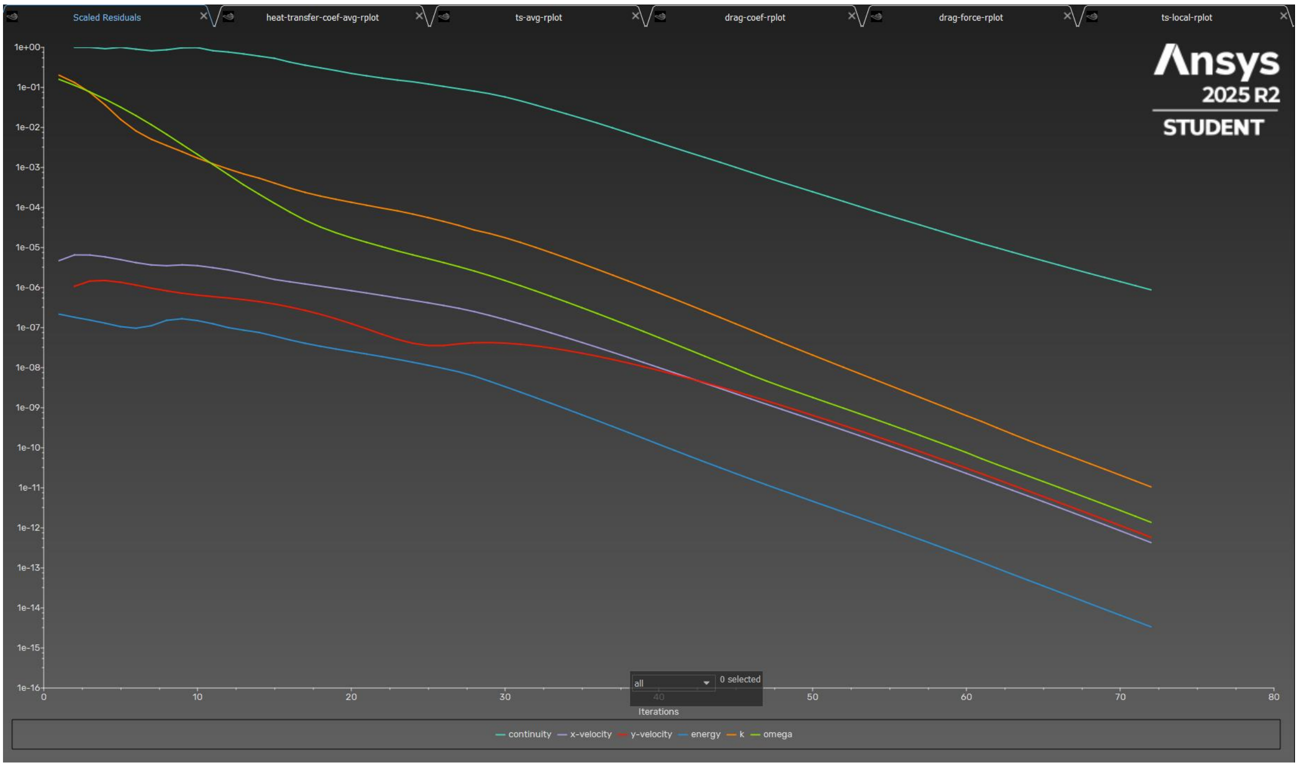

Figure 14.3: Scaled Residuals Curve (ANSYS Fluent)

NUMERICAL RESULTS

Coarse Mesh (Element Size: 0.10 m):

- Solutions are after an average of 133 iterations.

x (m)	Ts @ 20 km/h	Ts @ 40 km/h	Ts @ 60 km/h	Ts @ 80 km/h	Ts @ 100 km/h	Ts @ 120 km/h	Ts @ 140 km/h
0	34.156	27.76	25.43	24.21	23.45	22.94	22.56
1	32.729	27.18	25.11	24	23.31	22.83	22.48
2	32.384	27.03	25.02	23.95	23.27	22.81	22.46
3	32.507	27.09	25.07	23.99	23.31	22.84	22.49
4	32.848	27.26	25.18	24.07	23.38	22.9	22.54
5	33.284	27.48	25.33	24.18	23.47	22.97	22.61
6	33.746	27.72	25.49	24.31	23.56	23.05	22.68
7	34.403	28.07	25.73	24.48	23.71	23.17	22.78
8	34.59	28.17	25.79	24.54	23.75	23.21	22.81

Figure 15.1: Ts vs x Table (Excel)

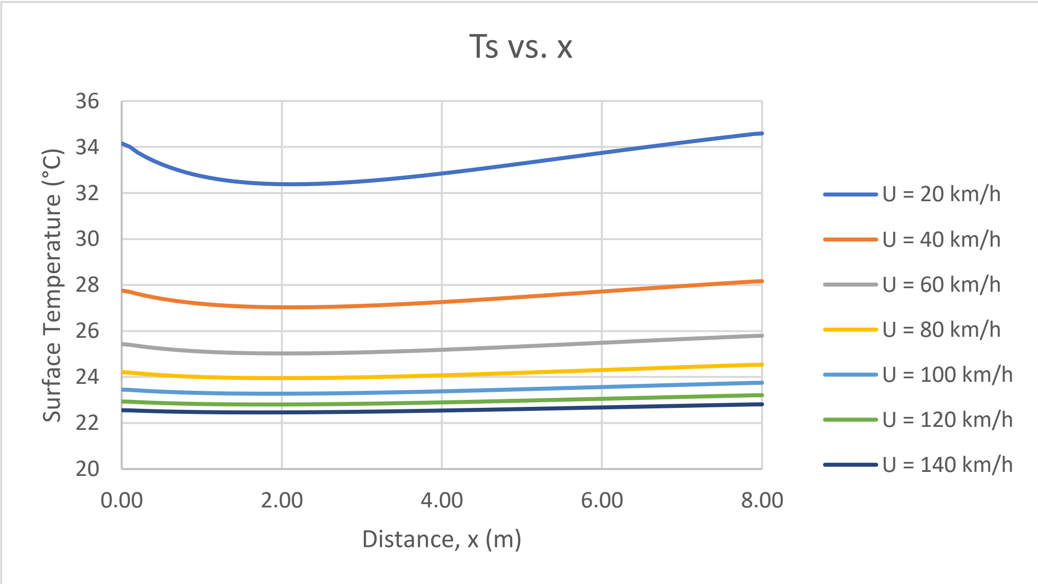

Figure 15.2: Requirement [1] (Excel)

Velocity (U) (km/h)	Surface Average Temperature (Ts, avg) (°C)	Overall Convection Coefficient (h, avg) (W/m²·K)	Friction Force (Fd) (N)	Overall Skin Friction Coefficient (Cd, avg)
20	33.233	15.155	1.3749	0.0036364
40	27.45	26.904	4.8884	0.0032324
60	25.302	37.793	10.307	0.003029
80	24.159	48.176	17.525	0.0028971
100	23.442	58.207	26.476	0.0028011
120	22.948	67.972	37.11	0.0027265
140	22.585	77.524	49.389	0.0026659

Figure 15.3: Requirement Results (Excel)

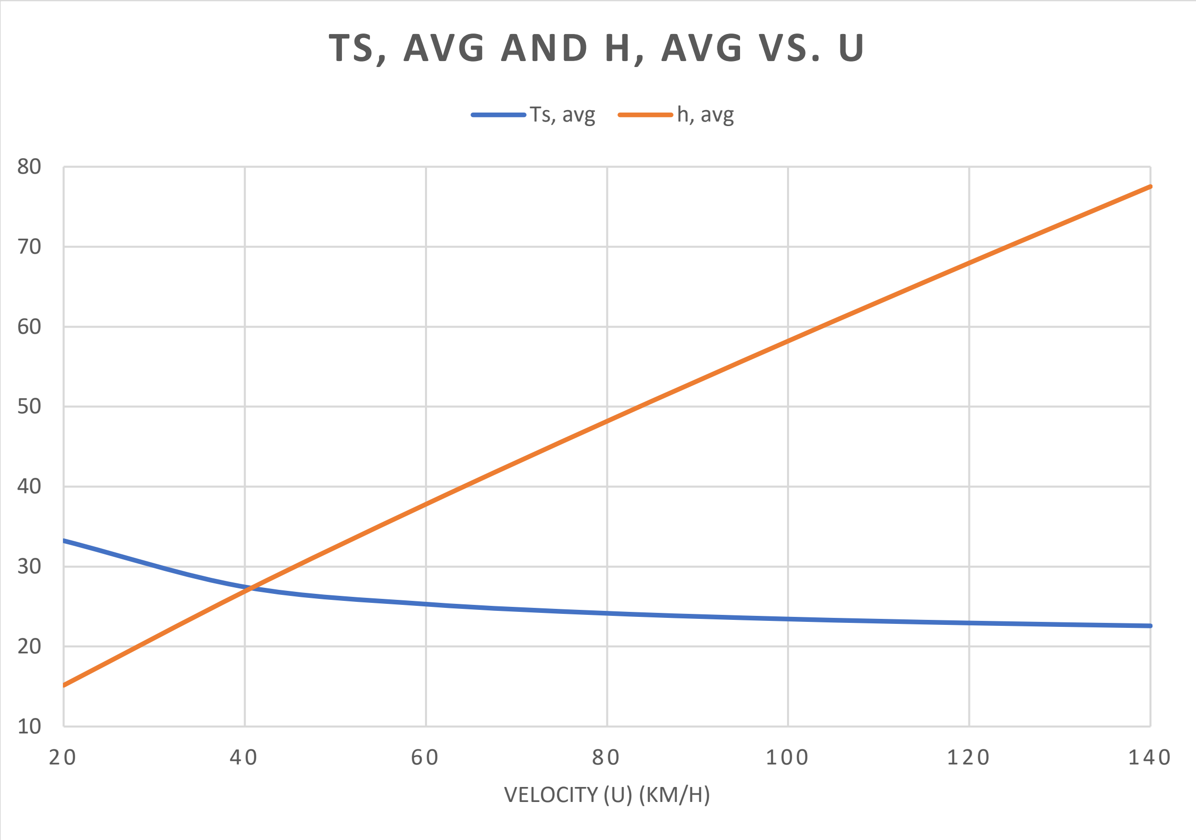

Figure 15.4: Requirement [2] *(Excel)*

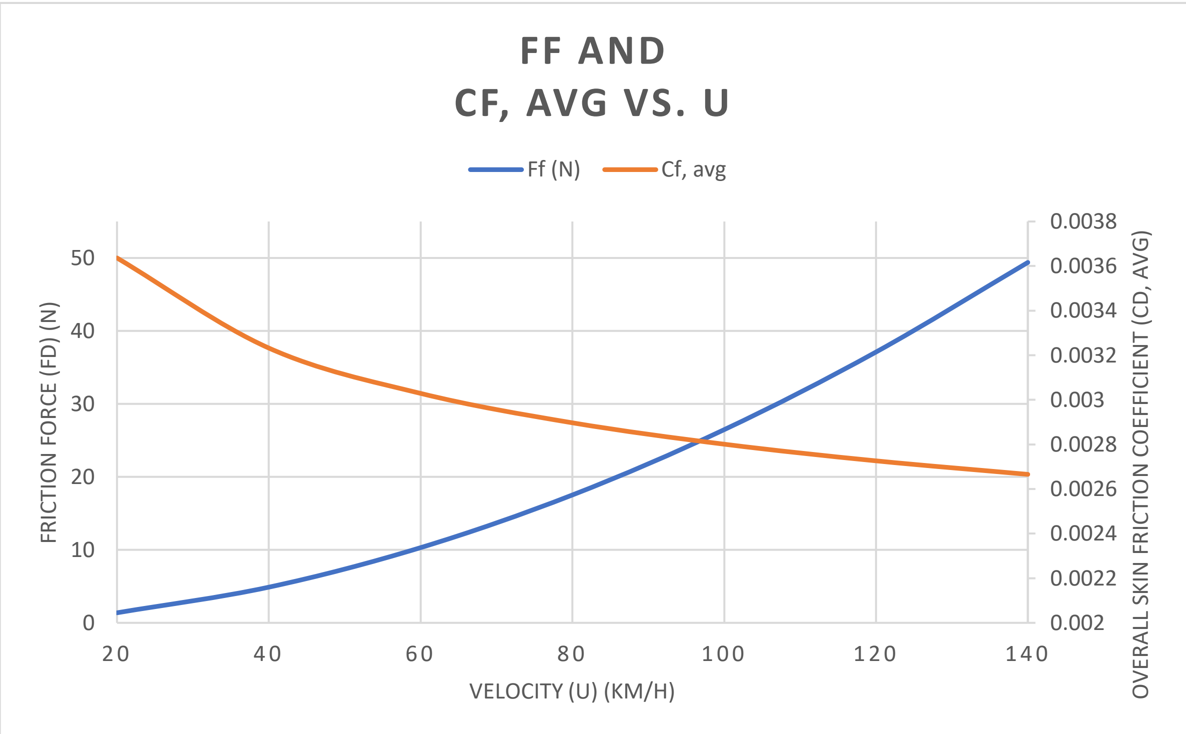

Figure 15.5: Requirement [3] *(Excel)*

Medium Mesh (Element Size: 0.05 m):

- Solutions are after an average of 79 iterations.

x (m)	Ts @ 20 km/h	Ts @ 40 km/h	Ts @ 60 km/h	Ts @ 80 km/h	Ts @ 100 km/h	Ts @ 120 km/h	Ts @ 140 km/h
0	32.74	27.08	24.98	23.88	23.19	22.72	22.37
1	30.77	26.19	24.45	23.52	22.92	22.51	22.21
2	31.32	26.47	24.63	23.64	23.01	22.58	22.26
3	32.22	26.92	24.94	23.88	23.22	22.76	22.42
4	32.93	27.3	25.21	24.09	23.39	22.9	22.54
5	33.61	27.67	25.46	24.28	23.54	23.03	22.66
6	34.19	28	25.69	24.45	23.68	23.15	22.76
7	34.75	28.27	25.87	24.6	23.8	23.25	22.85
8	35.12	28.47	26.01	24.71	23.89	23.32	22.91

Figure 16.1: Ts vs x Table (Excel)

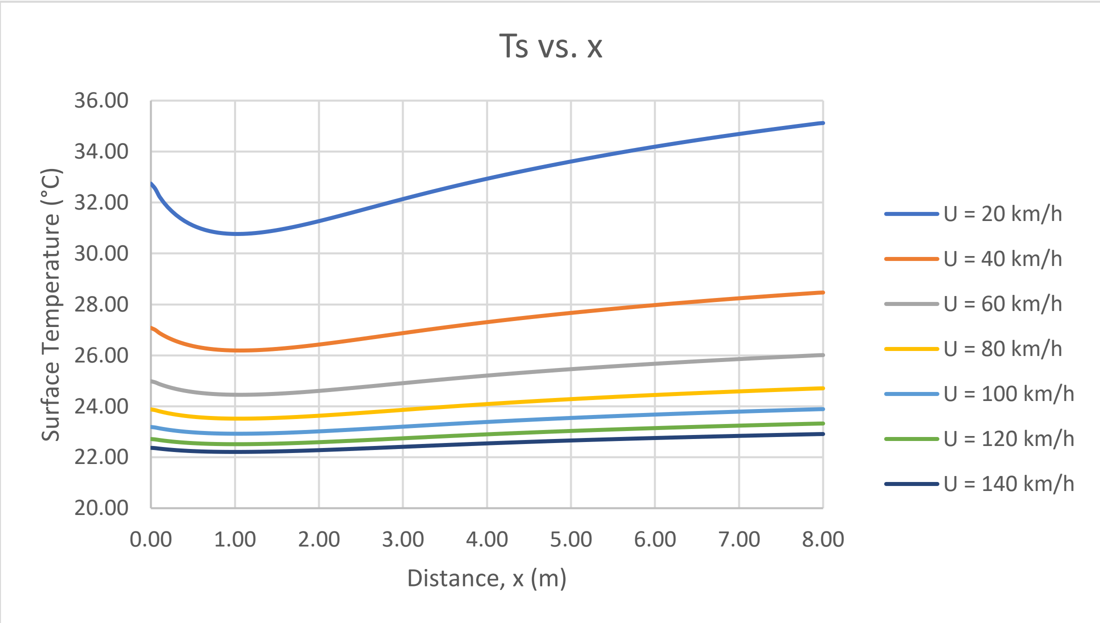

Figure 16.2: Requirement [1] (Excel)

Velocity (U) (km/h)	Surface Average Temperature (Ts, avg) (°C)	Overall Convection Coefficient (h, avg) (W/m²·K)	Friction Force (Fd) (N)	Overall Skin Friction Coefficient (Cd, avg)
20	32.883	15.717	1.4209	0.0037581
40	27.281	27.761	5.0329	0.0033279
60	25.192	38.902	10.592	0.0031128
80	24.078	49.513	17.99	0.0029738
100	23.377	59.763	27.157	0.0028731
120	22.893	69.747	38.049	0.0027954
140	22.537	79.498	50.613	0.002732

Figure 16.3: Requirement Results (Excel)

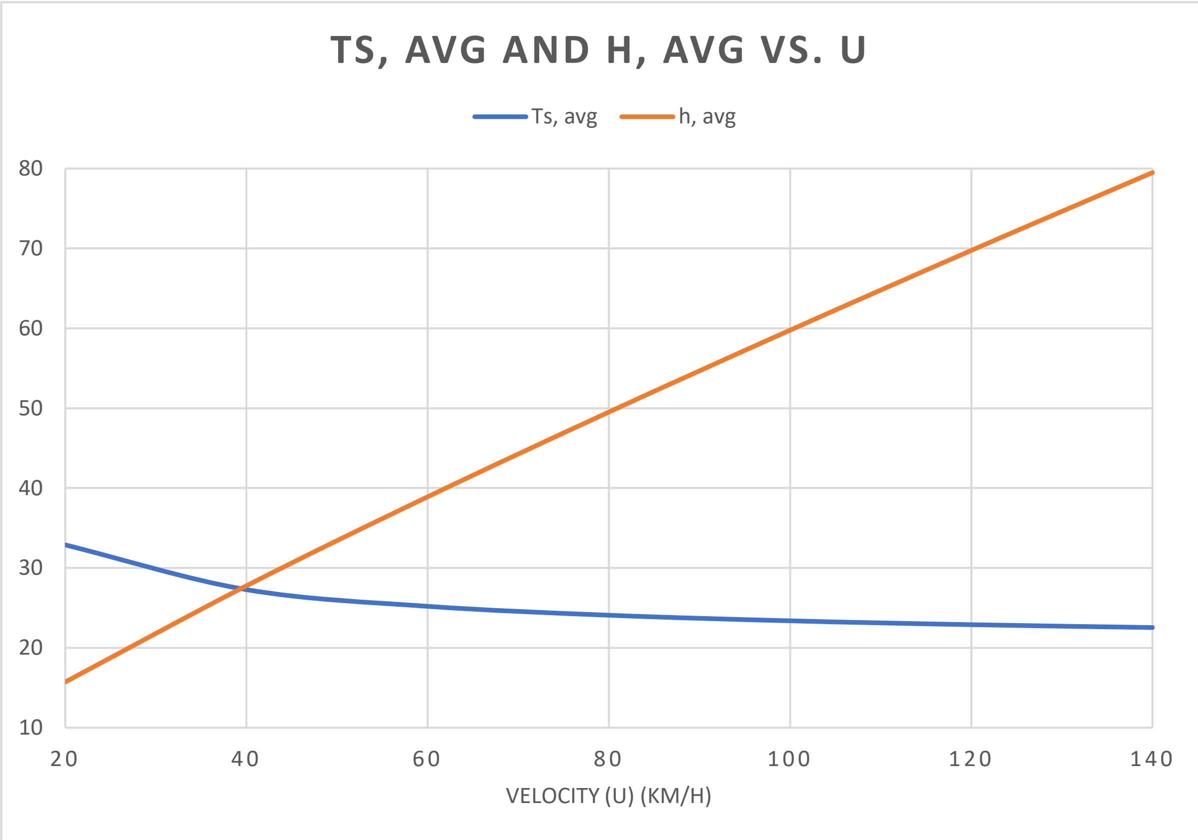

Figure 16.4: Requirement [2] (Excel)

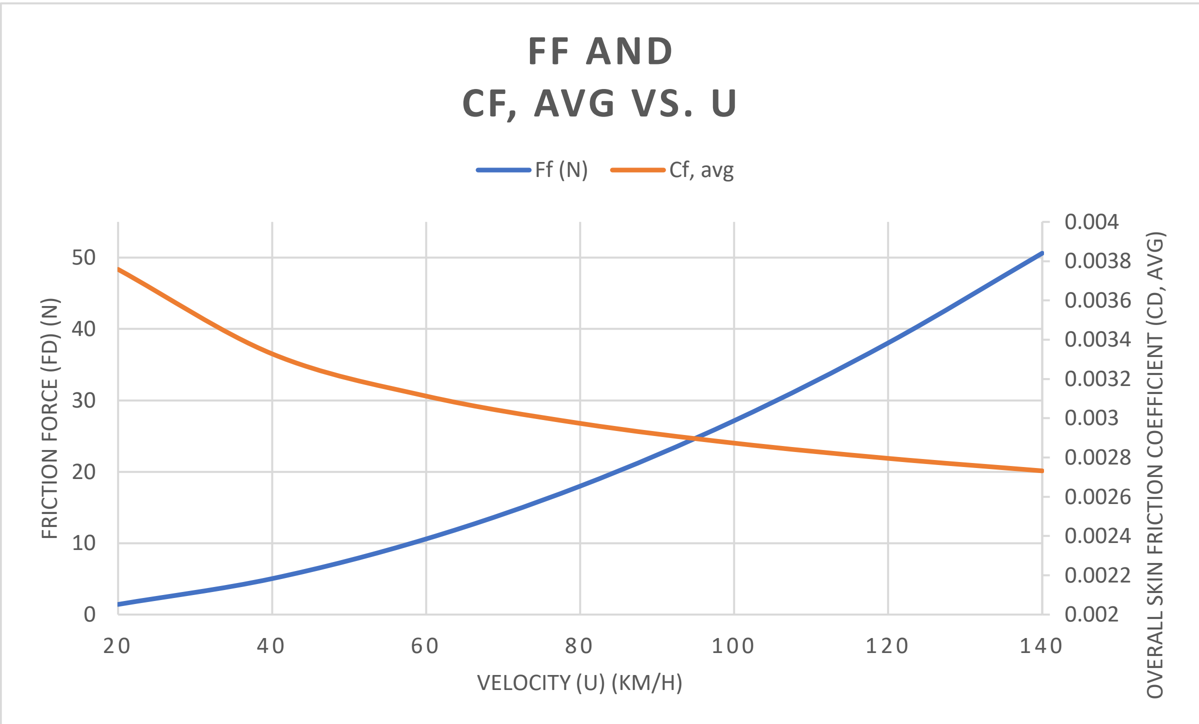

Figure 16.5: Requirement [3] (Excel)

Fine Mesh (Element Size: 0.02 m):

- Solutions are after an average of 74 iterations.

x (m)	Ts @ 20 km/h	Ts @ 40 km/h	Ts @ 60 km/h	Ts @ 80 km/h	Ts @ 100 km/h	Ts @ 120 km/h	Ts @ 140 km/h
0	30.61	26.13	24.38	23.43	22.83	22.42	22.12
1	29.71	25.6	24.04	23.19	22.66	22.29	22.01
2	31.45	26.54	24.69	23.69	23.07	22.63	22.31
3	32.67	27.18	25.13	24.03	23.34	22.87	22.52
4	33.57	27.65	25.45	24.28	23.54	23.04	22.66
5	34.31	28.03	25.71	24.47	23.7	23.17	22.78
6	34.91	28.34	25.92	24.64	23.84	23.28	22.88
7	35.42	28.61	26.11	24.78	23.95	23.38	22.96
8	35.87	28.85	26.27	24.9	24.05	23.46	23.03

Figure 17.1: Ts vs x Table (Excel)

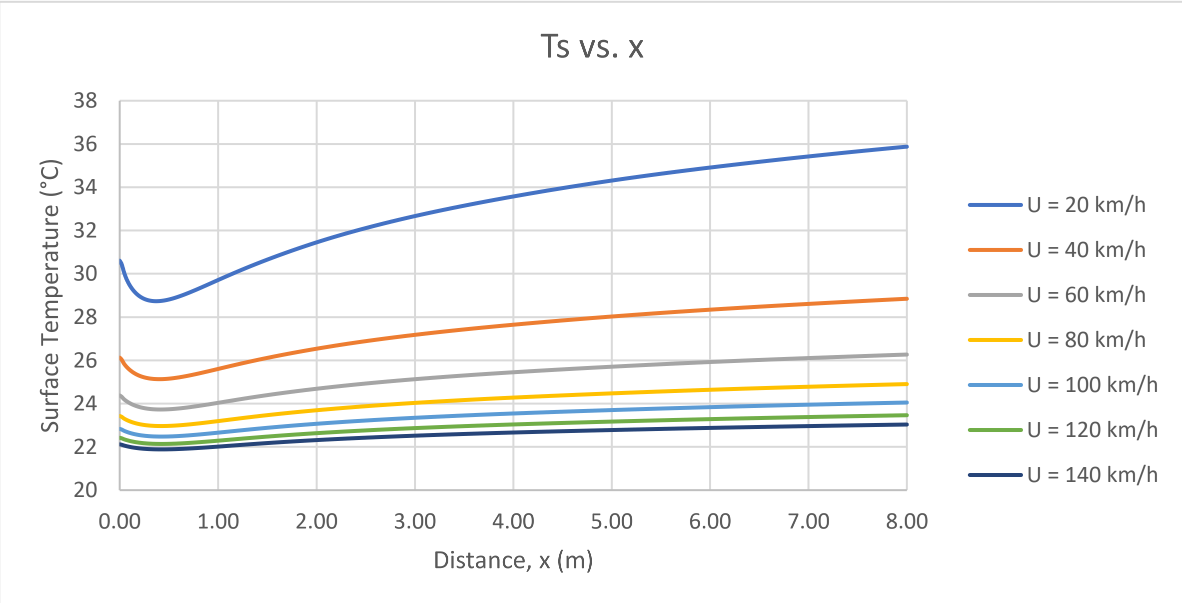

Figure 17.2: Requirement [1] (Excel)

Velocity (U) (km/h)	Surface Average Temperature (Ts, avg) (°C)	Overall Convection Coefficient (h, avg) (W/m²·K)	Friction Force (Fd) (N)	Overall Skin Friction Coefficient (Cd, avg)
20	33.055	15.807	1.4100	0.0037292
40	27.373	27.851	4.9965	0.0033038
60	25.259	38.962	10.513	0.003095
80	24.131	49.531	17.849	0.002956
100	23.423	59.724	26.935	0.0028496
120	22.934	69.633	37.719	0.0027712
140	22.575	79.313	50.159	0.0027075

Figure 17.3: Requirement Results (Excel)

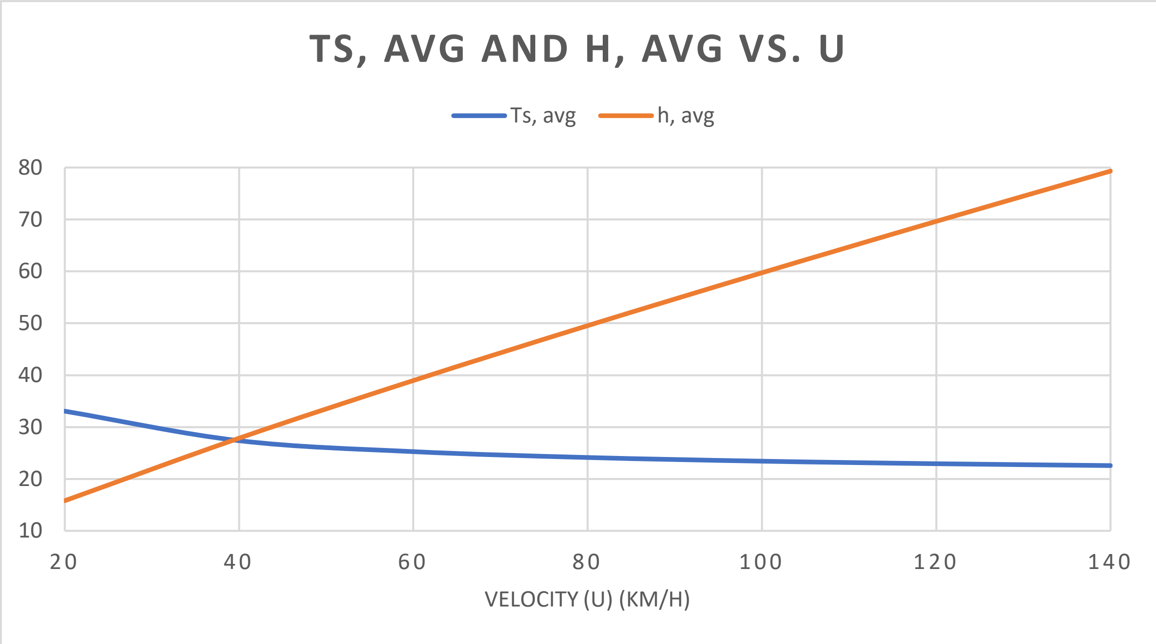

Figure 17.4: Requirement [2] (Excel)

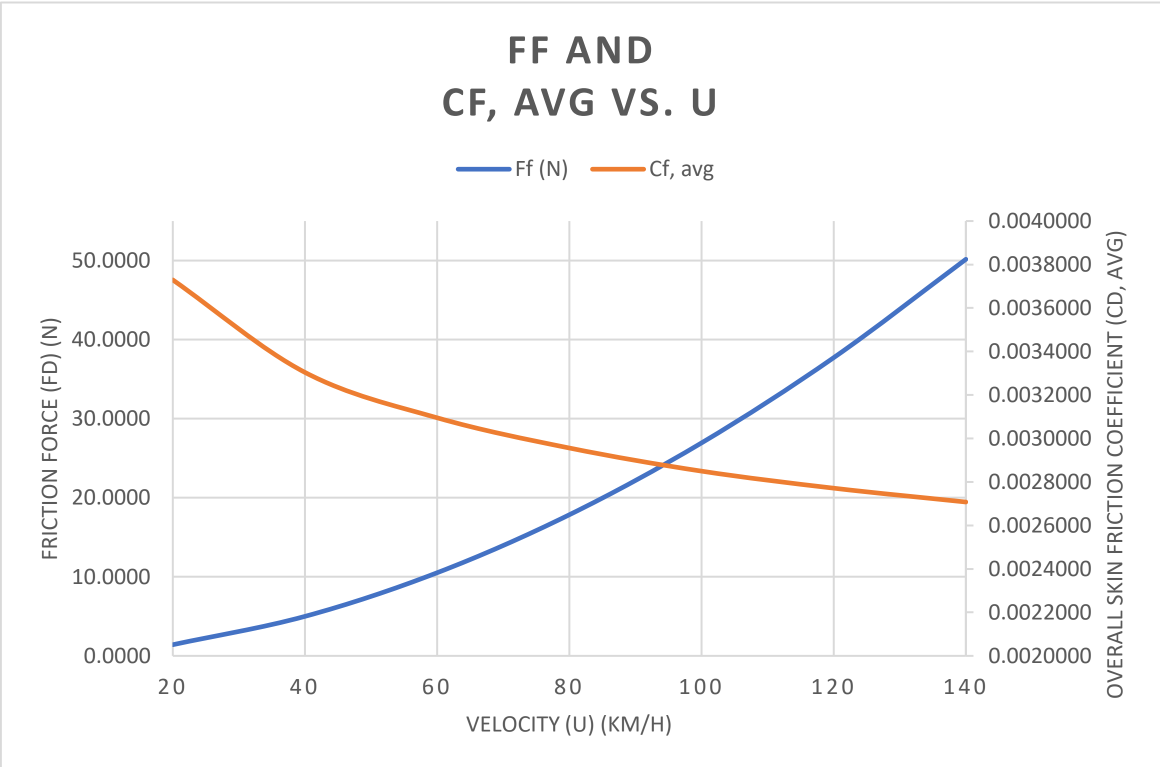

Figure 17.5: Requirement [3] (Excel)

MESH INDEPENDENCE STUDY

A mesh independence study was performed to determine the mesh density required to obtain accurate and stable CFD results for the flow over the heated flat plate. Three systematically refined meshes were generated—**Coarse**, **Medium**, and **Fine**—by reducing the global element size from 0.10 m to 0.02 m while maintaining consistent inflation layers and domain geometry.

The accuracy of each mesh was evaluated by comparing predicted thermal and aerodynamic quantities at several inlet velocities. The primary criteria used for comparison were:

- **Surface Average Temperature, Ts, avg (°C)**
- **Overall Convection Heat Transfer Coefficient, h, avg (W/m²·K)**
- **Friction Force, Fd (N)**
- **Overall Skin Friction Coefficient, Cd**

To provide a fair benchmark, mesh comparison was conducted at **80 km/h**, which represents the midpoint of the investigated velocity range.

Mesh Comparison at 80 km/h:

Mesh	Surface Average Temperature (Ts, avg) (°C)	Overall Convection Coefficient (h, avg) (W/m²·K)	Friction Force (Fd) (N)	Overall Skin Friction Coefficient (Cd, avg)
Coarse	24.159	48.176	17.525	0.0028971
Medium	24.078	49.513	17.99	0.0029738
Fine	24.131	49.531	17.849	0.002956

Figure 18.1: Mesh Comparison (Excel)

Numerical Deviation Analysis:

To quantify the sensitivity of the solution to mesh refinement, deviations were computed relative to the **Fine mesh**, which is treated as the reference.

Mesh	Surface Average Temperature (Ts, avg) (°C)	Overall Convection Coefficient (h, avg) (W/m²·K)	Friction Force (Fd) (N)	Overall Skin Friction Coefficient (Cd, avg)
Coarse → Fine deviation	(24.159 – 24.131) / 24.131 = **0.12%**	(48.176 – 49.531) / 49.531 = **2.73%**	(17.525 – 17.849) / 17.849 = **1.81%**	(0.0028971 – 0.002956)/ 0.002956 = **1.99%**
Medium → Fine deviation:	(24.078 – 24.131) / 24.131 = 0.22%	(49.513 – 49.531) / 49.531 = **0.036%**	(17.990 – 17.849)/ 17.849 = **0.79%**	(0.0029738 – 0.002956)/ 0.002956 = **0.60%**

Figure 18.2: Numerical Deviation (Excel)

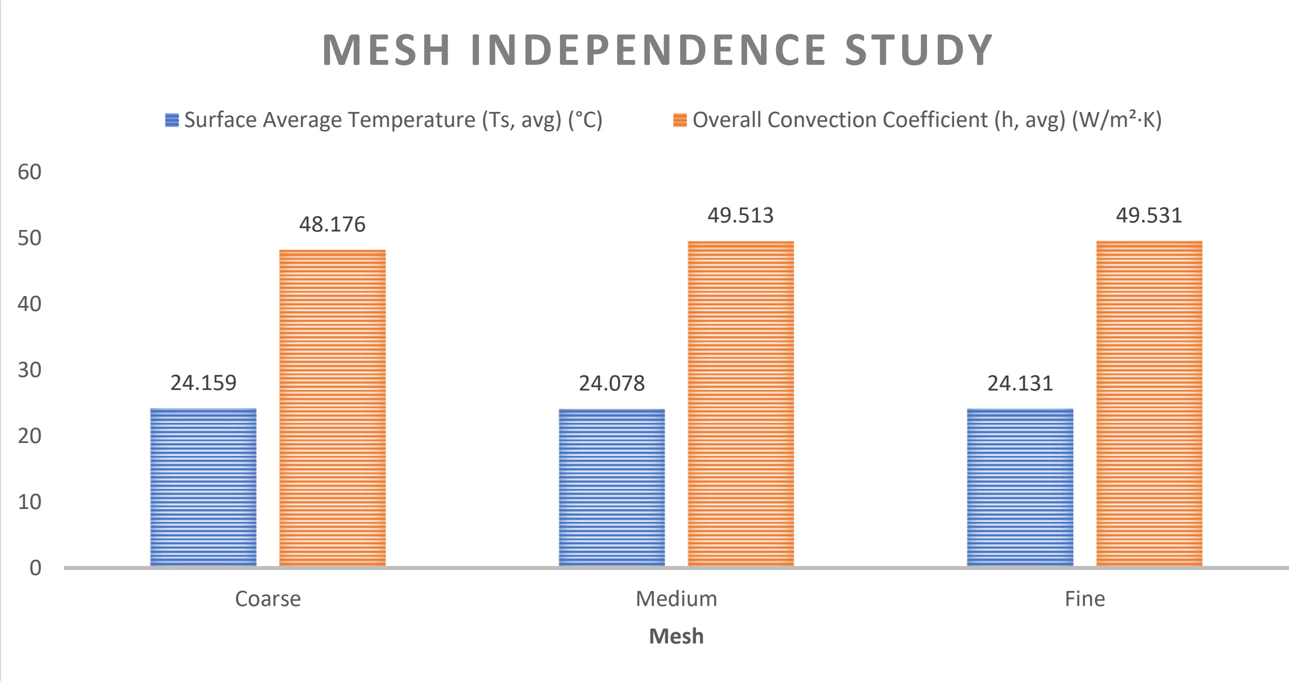

Figure 18.3: Mesh Independence Study Graph *(Excel)*

Interpretation of Results:

The Medium and Fine meshes provide very similar predictions for all quantities, with deviations consistently below **1%**. In contrast, the Coarse mesh exhibits noticeably larger deviations, particularly in heat transfer and friction predictions, indicating insufficient resolution of the boundary layer.

More importantly, **the Fine mesh provides the smoothest and most accurate temperature distribution along the plate**, especially in the leading-edge region where gradients are steep. This accurate boundary layer representation is essential for a heat-transfer-focused study.

Given the precision gains and the negligible deviation of Medium → Fine, the **Fine mesh is selected** as the final mesh for all simulations.

Final Statement:

The mesh independence analysis confirms that the **Fine mesh (element size = 0.02 m)** provides the most reliable and physically accurate solution. All thermal and aerodynamic results used in this study are therefore based on the Fine mesh.

EMPIRICAL SOLUTION

- The empirical model assumes fully turbulent flow over the entire plate length, whereas the CFD solution resolves the laminar-to-turbulent transition. This simplification introduces small deviations in predicted surface temperature and heat transfer coefficient.
- The incident solar radiation was taken as $G = 1000$ W/m^2, as specified in the problem statement. The absorbed heat flux was calculated using the surface absorptivity ($\alpha = 0.2$), resulting in a uniform absorbed heat flux of $q'' = 200$ W/m^2.

EES Code:

- 1st Requirement

```
==============================Geometry & constants==============================
L = 8        [m]
W = 2.5      [m]
A = L*W

G = 1000     [W/m^2]
alpha = 0.2
q_abs = alpha*G

T_inf = 293  [K]
P = 101325   [Pa]
==============================Velocity (manual for plotting)==============================
U_kmh = 140        [km/h]
U = U_kmh/3.6      [m/s]
==============================Air properties (film temp)==============================
T_film = T_inf

rho = density(Air, T=T_film, P=P)
mu  = viscosity(Air, T=T_film)
k   = conductivity(Air, T=T_film)
Pr  = prandtl(Air, T=T_film)
==============================Average quantities==============================
Re_L = rho*U*L/mu
Nu_L = 0.0308*Re_L^0.8*Pr^(1/3)

h_avg = Nu_L*k/L

Ts_avg = T_inf + q_abs/h_avg     [K]
Ts_avg_C = Ts_avg - 273.15       [C]
```

```
==============================Local distributions==============================
N = 50
x_min = 0.01*L
Duplicate i = 1, N
  x[i] = x_min + (i-1)*(L-x_min)/(N-1)
  Re_x[i] = rho*U*x[i]/mu
  Nu_x[i] = 0.0296*Re_x[i]^0.8*Pr^(1/3)
  h_x[i] = Nu_x[i]*k/x[i]
  Ts_x[i] = T_inf + q_abs/h_x[i] [K]
  Ts_x_C[i] = Ts_x[i] - 273.15   [C]
```

- 2nd and 3rd Requirements

```
====================GEOMETRY & LOAD====================
L = 8        [m]
W = 2.5      [m]
A = L*W
G = 1000     [W/m^2]
alpha = 0.2
q_flux = alpha*G
T_inf = 293  [K]
P = 101325   [Pa]
====================VELOCITY (PARAM) ====================
U = U_kmh*1000/3600   [m/s]
====================INITIAL GUESS ONLY====================
Ts_guess = 310   [K]
 ====================AIR PROPERTIES====================
T_film = (T_inf + Ts_guess)/2   [K]
rho = density(Air, T=T_film, P=P)
mu  = viscosity(Air, T=T_film)
k   = conductivity(Air, T=T_film)
Pr  = prandtl(Air, T=T_film)
====================FLOW PARAMETERS====================
Re_L = rho*U*L/mu
" Turbulent flat-plate correlation "
Nu_L = 0.0308*Re_L^(4/5)*Pr^(1/3)
h_avg = Nu_L*k/L
====================SURFACE TEMPERATURE====================
Ts_avg = T_inf + q_flux/h_avg
Ts_avg_C = Ts_avg - 273.15   [C]
====================SKIN FRICTION====================
Cf = 0.074/Re_L^0.2
F_f = 0.5*rho*U^2*Cf*A
```

Results:

- Ts, local Vs x

x (m)	Ts @ 20 km/h	Ts @ 40 km/h	Ts @ 60 km/h	Ts @ 80 km/h	Ts @ 100 km/h	Ts @ 120 km/h	Ts @ 140 km/h
0	32.74	27.08	24.98	23.88	23.19	22.72	22.37
1	30.77	26.19	24.45	23.52	22.92	22.51	22.21
2	31.27	26.42	24.61	23.63	23.02	22.59	22.28
3	32.14	26.87	24.91	23.86	23.2	22.74	22.41
4	32.93	27.3	25.21	24.09	23.39	22.9	22.54
5	33.61	27.67	25.46	24.28	23.54	23.03	22.66
6	34.19	27.97	25.67	24.45	23.68	23.14	22.76
7	34.69	28.24	25.85	24.59	23.79	23.24	22.84
8	35.12	28.47	26.01	24.71	23.89	23.32	22.91

Figure 19.1: Ts vs x Table (EES)

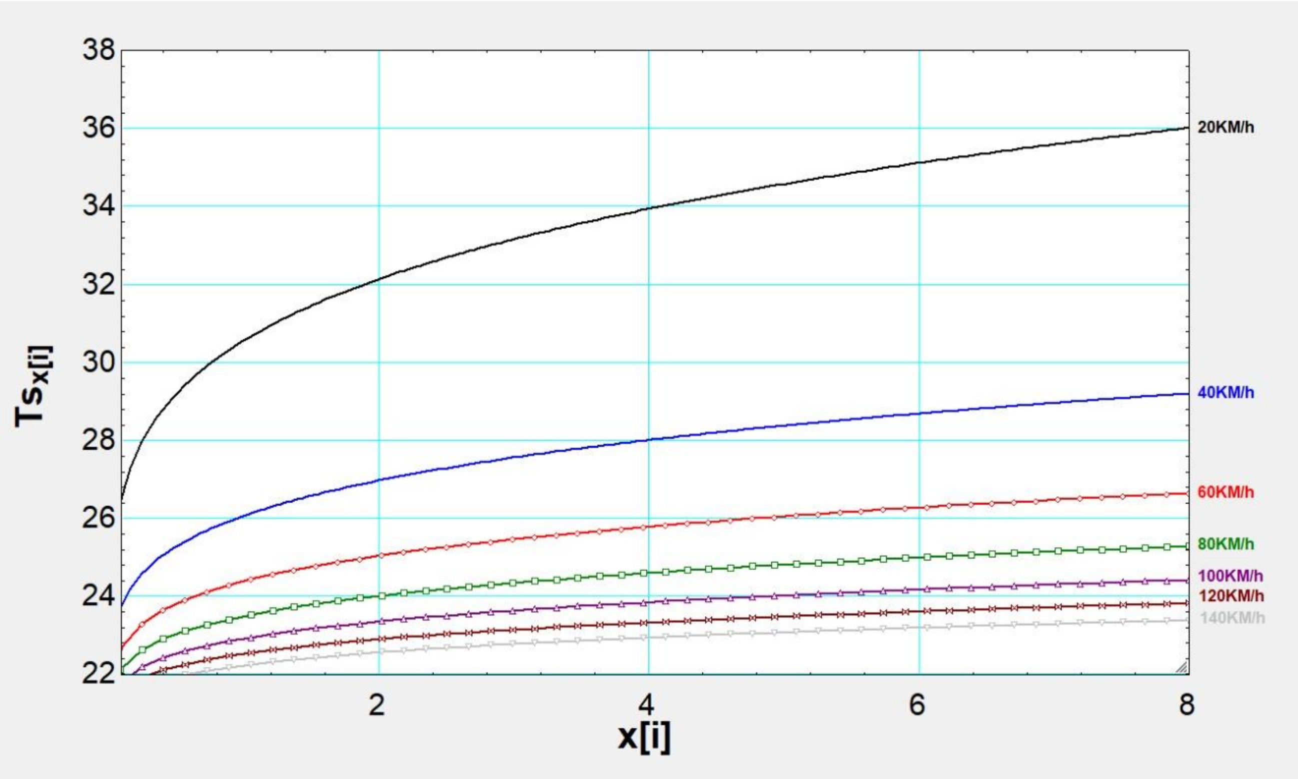

Figure 19.2: Ts vs x Curve (EES)

- Ts, avg and h, avg Vs U

Velocity (U) (km/h)	Surface Average Temperature (Ts, avg) (°C)	Overall Convection Coefficient (h, avg) (W/m²·K)
20	35.49	12.79
40	28.83	22.27
60	26.34	30.8
80	25.01	38.77
100	24.16	46.35
120	23.58	53.63
140	23.15	60.67

Figure 20.1: Ts, avg and h, avg Vs U Table (EES)

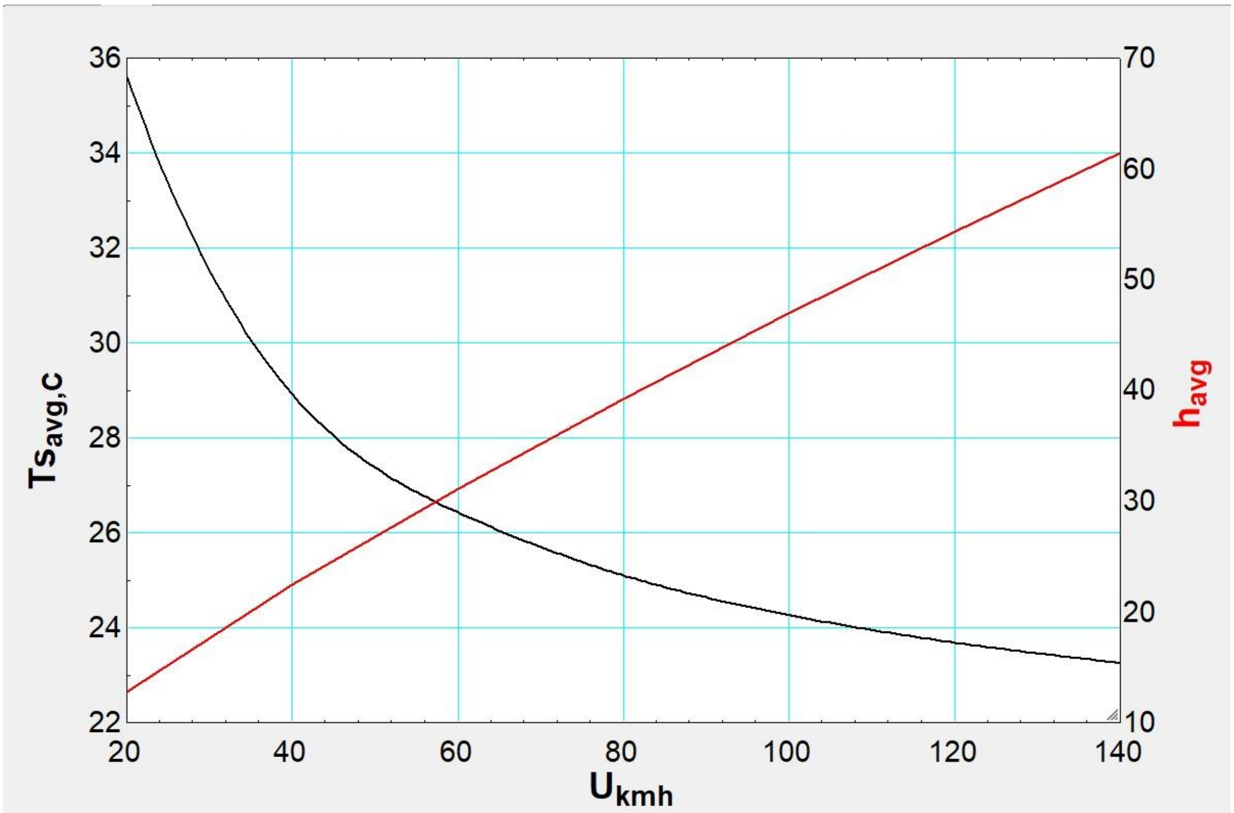

Figure 20.2: Ts, avg and h, avg Vs U Curve (EES)

- Fd and Cd Vs U

Velocity (U) (km/h)	Friction Force (Fd) (N)	Overall Skin Friction Coefficient (Cd, avg)
20	1.374	0.003803
40	4.785	0.00331
60	9.927	0.003052
80	16.66	0.002882
100	24.9	0.002756
120	34.57	0.002657
140	45.62	0.002577

Figure 21.1: Fd and Cd, avg Vs U Table (EES)

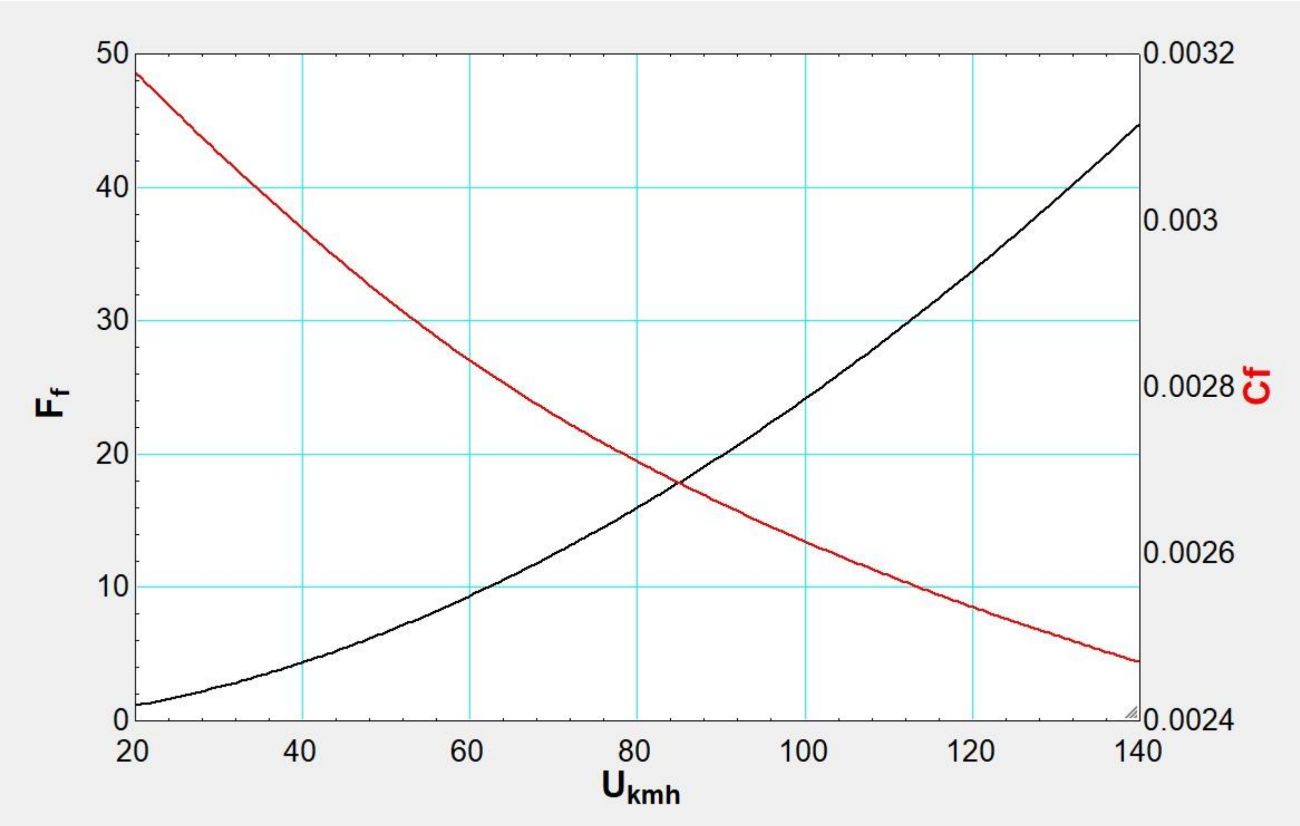

Figure 21.2: Fd and Cd, avg Vs U Curve (EES)

NUMERICAL VS. EMPIRICAL COMPARISON

- The below comparison is done between the Numerical Results generated using the fine meshing and the Empirical Results from EES.

Local surface Temperature Vs. Distance (x):

- Comparison is done on a single velocity of 80 km/h.
- A quantitative error analysis was performed between the numerical and empirical local surface temperature distributions. The mean absolute error (MAE) was found to be 0.218 °C, while the mean signed error (MSE) was −0.044 °C, indicating a very small overall under-prediction by the numerical model. The mean absolute percentage error (MAPE) was 0.91%, confirming excellent agreement between the CFD results and the empirical flat-plate correlations.

x (m)	Ts (Numerical)	Ts (Empirical)	Absolute Error (°C)	% Error
0	23.43	23.88	0.45	1.88%
1	23.19	23.52	0.33	1.40%
2	23.69	23.63	0.06	0.25%
3	24.03	23.86	0.17	0.71%
4	24.28	24.09	0.19	0.79%
5	24.47	24.28	0.19	0.78%
6	24.64	24.45	0.19	0.78%
7	24.78	24.59	0.19	0.77%
8	24.9	24.71	0.19	0.77%

Figure 22.1: Ts, local Vs. x Comparison Table (Excel)

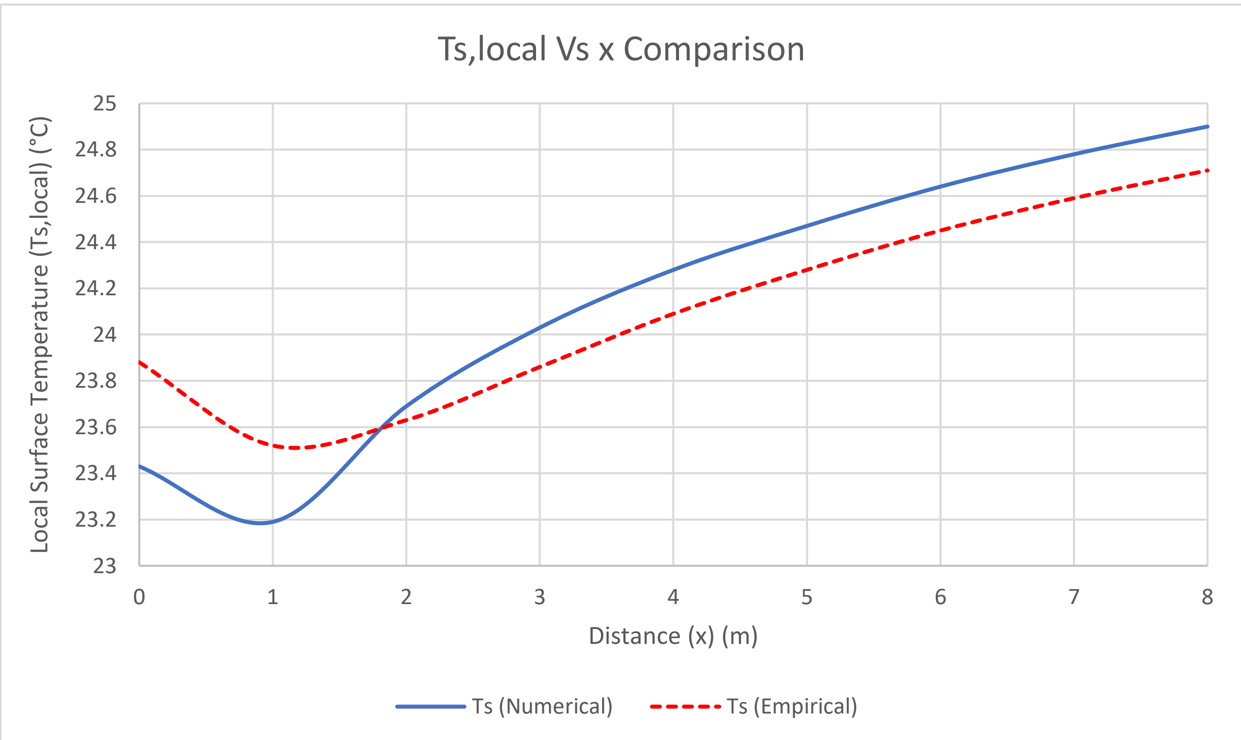

Figure 22.2: Ts, local Vs. x Comparison Curve (Excel)

Surface Average Temperature and Overall Convection Coefficient Vs. Velocity:

- For the average surface temperature comparison, the numerical model exhibited a mean absolute error (MAE) of 1.12 °C and a mean signed error (MSE) of −1.12 °C, indicating a consistent but moderate under-prediction relative to empirical correlations. The mean absolute percentage error (MAPE) was 3.97%, demonstrating good agreement across the investigated velocity range.
- In contrast, the average convection coefficient showed a higher deviation, with an MAE of 10.79 W/m²·K and a MAPE of 27.48%. The numerical model consistently over-predicted the heat transfer coefficient, which is attributed to idealized flow assumptions and enhanced near-wall resolution in the CFD simulation compared to empirical flat-plate correlations.

Velocity (U) (km/h)	Ts, avg (°C) (Numerical)	Ts, avg (°C) (Empirical)	Absolute Error (°C)	% Error	h, avg (W/m²·K) (Numerical)	h, avg (W/m²·K) (Empirical)	Absolute Error (W/m²·K)	% Error
20	33.055	35.49	2.435	6.86%	15.807	12.79	3.017	23.59%
40	27.373	28.83	1.457	5.05%	27.851	22.27	5.581	25.06%
60	25.259	26.34	1.081	4.10%	38.962	30.8	8.162	26.50%
80	24.131	25.01	0.879	3.51%	49.531	38.77	10.761	27.76%
100	23.423	24.16	0.737	3.05%	59.724	46.35	13.374	28.85%
120	22.934	23.58	0.646	2.74%	69.633	53.63	16.003	29.84%
140	22.575	23.15	0.575	2.48%	79.313	60.67	18.643	30.73%

Figure 23.1: Ts, avg and h, avg Vs. U Comparison Table (Excel)

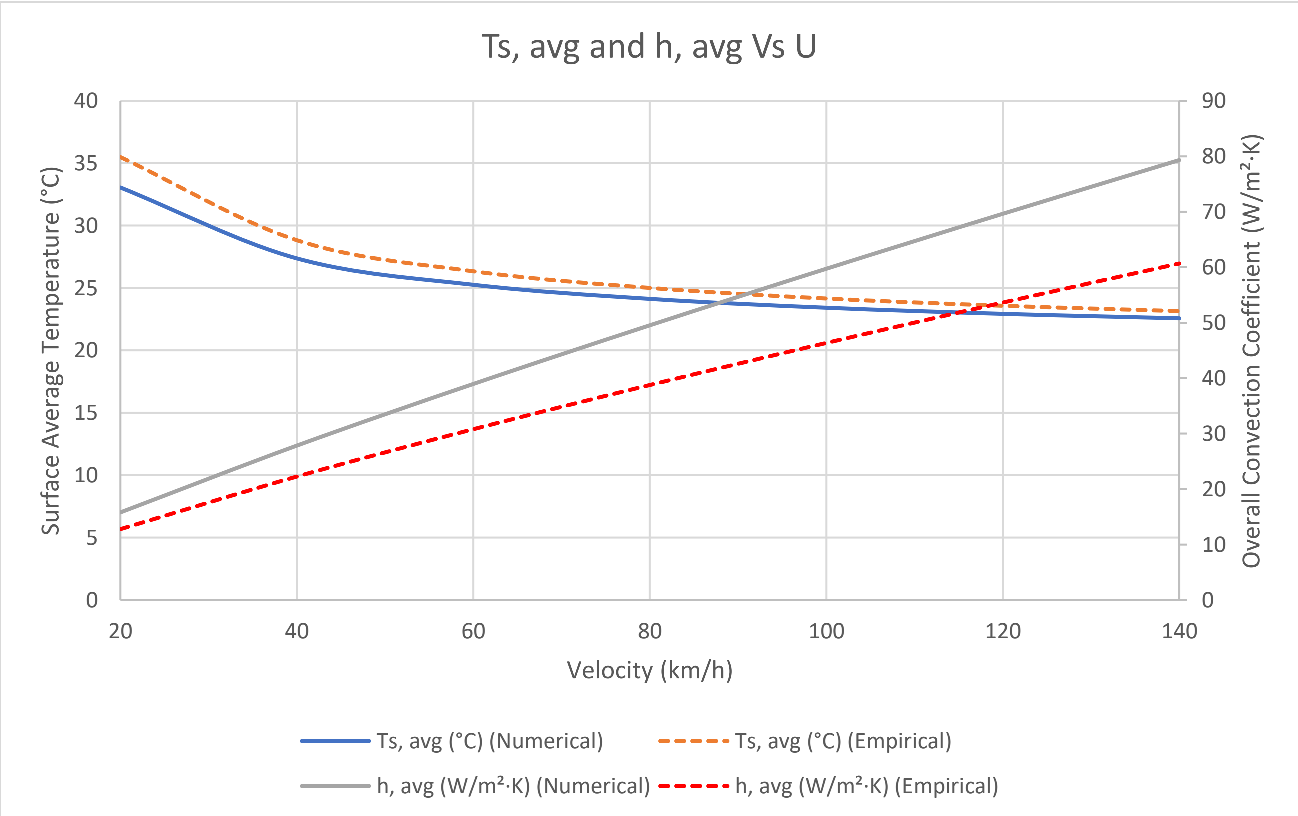

Figure 23.2: Ts, avg and h, avg Vs. U Comparison Curve (Excel)

Friction Force and Overall Skin Friction Coefficient Vs. Velocity:

- For the aerodynamic force comparison, the numerical model predicted the friction force with a mean absolute error (MAE) of 1.68 N and a mean absolute percentage error (MAPE) of 6.76% over the investigated velocity range. The positive mean signed error indicates a consistent but moderate over-prediction of drag force, which is expected due to the detailed resolution of viscous shear stresses in the CFD simulation.
- The average skin friction coefficient showed excellent agreement with empirical correlations, yielding a MAPE of only 2.70% and an absolute error on the order of 10^{-5}. This confirms the capability of the numerical model to accurately capture wall shear behavior across all flow velocities.

Velocity (U) (km/h)	Fd (N) (Numerical)	Fd (N) (Empirical)	Absolute Error (N)	% Error	Cd, avg (Numerical)	Cd, avg (Empirical)	Absolute Error	% Error
20	1.41	1.374	0.036	2.62%	0.0037292	0.003803	0.0000738	1.94%
40	4.9965	4.785	0.2115	4.42%	0.0033038	0.00331	0.0000062	0.19%
60	10.513	9.927	0.586	5.90%	0.003095	0.003052	0.0000430	1.41%
80	17.849	16.66	1.189	7.14%	0.002956	0.002882	0.0000740	2.57%
100	26.935	24.9	2.035	8.17%	0.0028496	0.002756	0.0000936	3.40%
120	37.719	34.57	3.149	9.11%	0.0027712	0.002657	0.0001142	4.30%
140	50.159	45.62	4.539	9.95%	0.0027075	0.002577	0.0001305	5.06%

Figure 24.1: Fd and Cd, avg Vs. U Comparison Table (Excel)

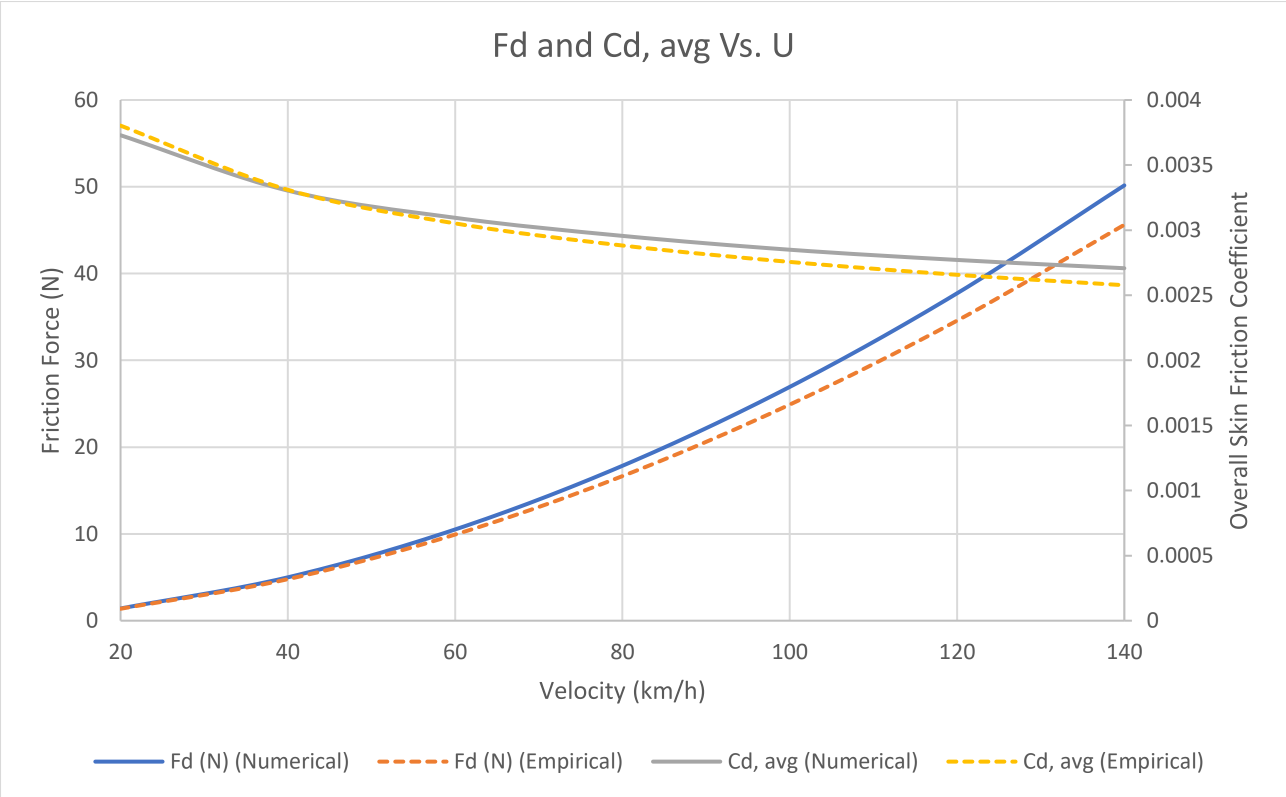

Figure 24.2: Fd and Cd, avg Vs. U Comparison Curve (Excel)

FINAL DISCUSSION AND CONCLUSIONS

This project presented a comprehensive numerical and analytical investigation of convective heat transfer and aerodynamic behavior over a flat plate subjected to solar radiation under external forced convection. The study combined Computational Fluid Dynamics (CFD) simulations using ANSYS Fluent with empirical correlations from classical heat transfer and fluid mechanics theory, enabling a rigorous validation of the numerical model.

A structured mesh independence study was first conducted using coarse, medium, and fine meshes. The results demonstrated that the fine mesh provided the most consistent and physically accurate predictions of surface temperature, heat transfer coefficient, and aerodynamic quantities. Numerical deviations between mesh levels were minimal, confirming grid convergence and justifying the selection of the fine mesh for all subsequent simulations.

For the first requirement, the local surface temperature distribution along the plate length showed excellent agreement between numerical and empirical results. The temperature variation followed the expected physical behavior, with higher temperatures near the leading edge due to thinner thermal boundary layers and gradual stabilization downstream. Quantitative comparison yielded very small discrepancies, with a mean absolute percentage error (MAPE) of approximately 1%, confirming the ability of the CFD model to accurately resolve local heat transfer behavior.

In the second requirement, the effects of flow velocity on the surface-average temperature and overall convection coefficient were examined. As expected, increasing velocity resulted in lower average surface temperatures and higher convection coefficients due to enhanced convective heat removal. The numerical predictions of surface-average temperature showed strong agreement with empirical solutions, with a MAPE of approximately 4%. The convection coefficient exhibited larger deviations (≈27%), which is consistent with known limitations of empirical correlations that rely on simplified boundary-layer assumptions and average flow properties, whereas CFD resolves local flow physics and turbulence effects.

The third requirement focused on aerodynamic performance through the evaluation of friction force and average skin friction coefficient. Both quantities increased systematically with velocity, in agreement with theoretical expectations. The numerical results demonstrated very good agreement with empirical correlations, yielding a MAPE of 6.76% for friction force and only 2.70% for the average skin friction coefficient. The observed slight overprediction of drag in the numerical model is attributed to the detailed resolution of viscous shear stresses and turbulence effects inherent to CFD simulations.

Overall, the numerical model successfully captured the fundamental thermal and aerodynamic phenomena governing external forced convection over a flat plate. The close agreement between CFD and empirical solutions across all project requirements confirms the validity, robustness, and physical consistency of the simulation setup. The study demonstrates that CFD, when supported by mesh independence verification and empirical validation, provides a powerful and reliable tool for analyzing coupled heat transfer and fluid flow problems encountered in real engineering applications.