CONVECTIVE HEAT TRANSFER & AERODYNAMIC FORCES ON A MOVING TRUCK CARTAGE

Heat Transfer (MEC 311)

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Prepared by:

Power of Heat

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Softwares Used: ANSYS Workbench, ANSYS Discovery, ANSYS Mechanical, ANSYS Fluent, Excel, MATLAB and EES

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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.

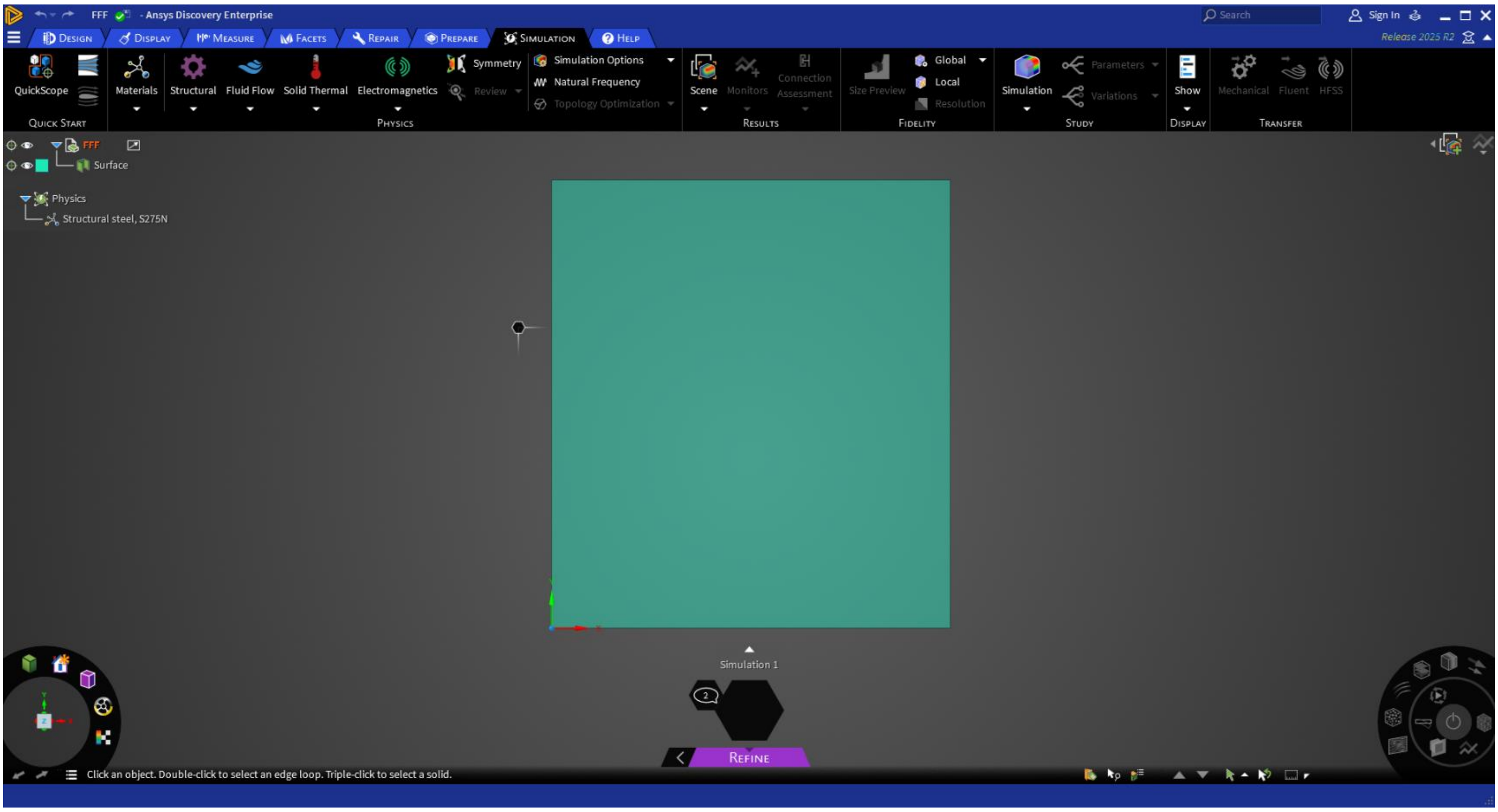

Figure 1: Geometry (ANSYS Discovery)

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):

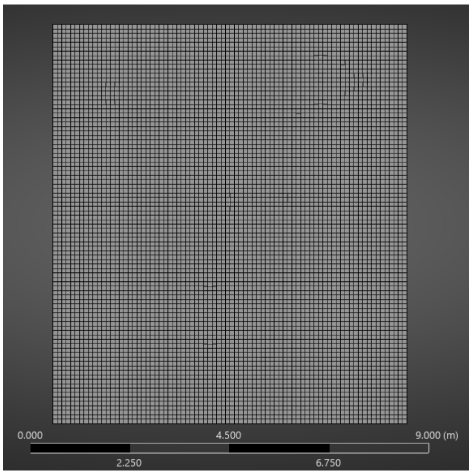

Figure 2.1: Mesh (ANSYS Mechanical)

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)

Details of "Inflation" - Inflation

Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Suppressed	No
Boundary Scoping Method	Named Selections
Boundary	truck cartage plate
Inflation Option	First Layer Thickness
First Layer Height	2.e-003 m
Maximum Layers	6
Growth Rate	1.25
Inflation Algorithm	Pre

Figure 2.4: Inflation Details (ANSYS Mechanical)

Medium Mesh (Element Size: 0.05 m):

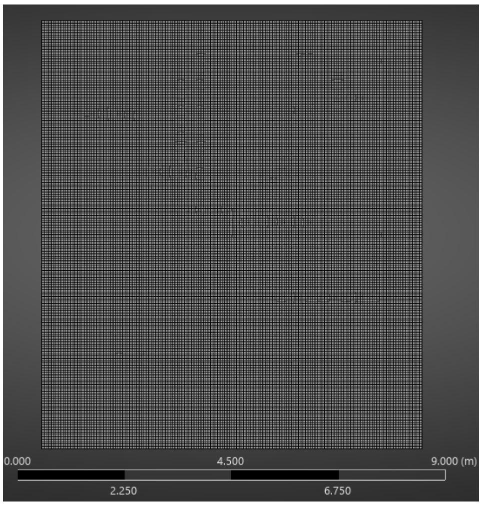

Figure 3.1: Mesh (ANSYS Mechanical)

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)*

Details of "Inflation" - Inflation

Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Suppressed	No
Boundary Scoping Method	Named Selections
Boundary	truck cartage plate
Inflation Option	First Layer Thickness
First Layer Height	1.e-003 m
Maximum Layers	8
Growth Rate	1.2
Inflation Algorithm	Pre

Figure 3.4: Inflation Details *(ANSYS Mechanical)*

Fine Mesh (Element Size: 0.02 m):

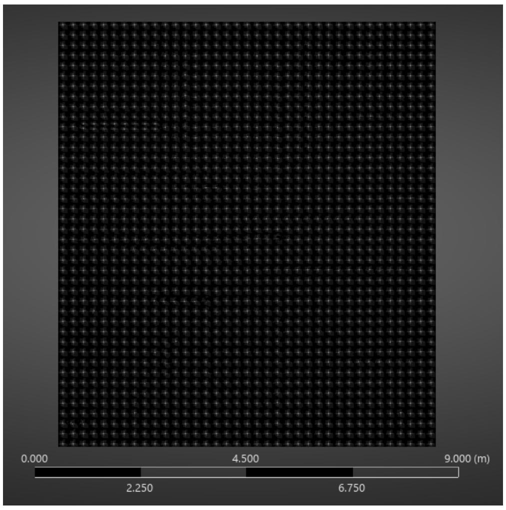

Figure 4.1: Mesh *(ANSYS Mechanical)*

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)*

Details of "Inflation" - Inflation

Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Suppressed	No
Boundary Scoping Method	Named Selections
Boundary	truck cartage plate
Inflation Option	First Layer Thickness
First Layer Height	5.e-004 m
Maximum Layers	10
Growth Rate	1.15
Inflation Algorithm	Pre

Figure 4.4: Inflation Details *(ANSYS Mechanical)*

PHYSICS SETUP

General Settings:

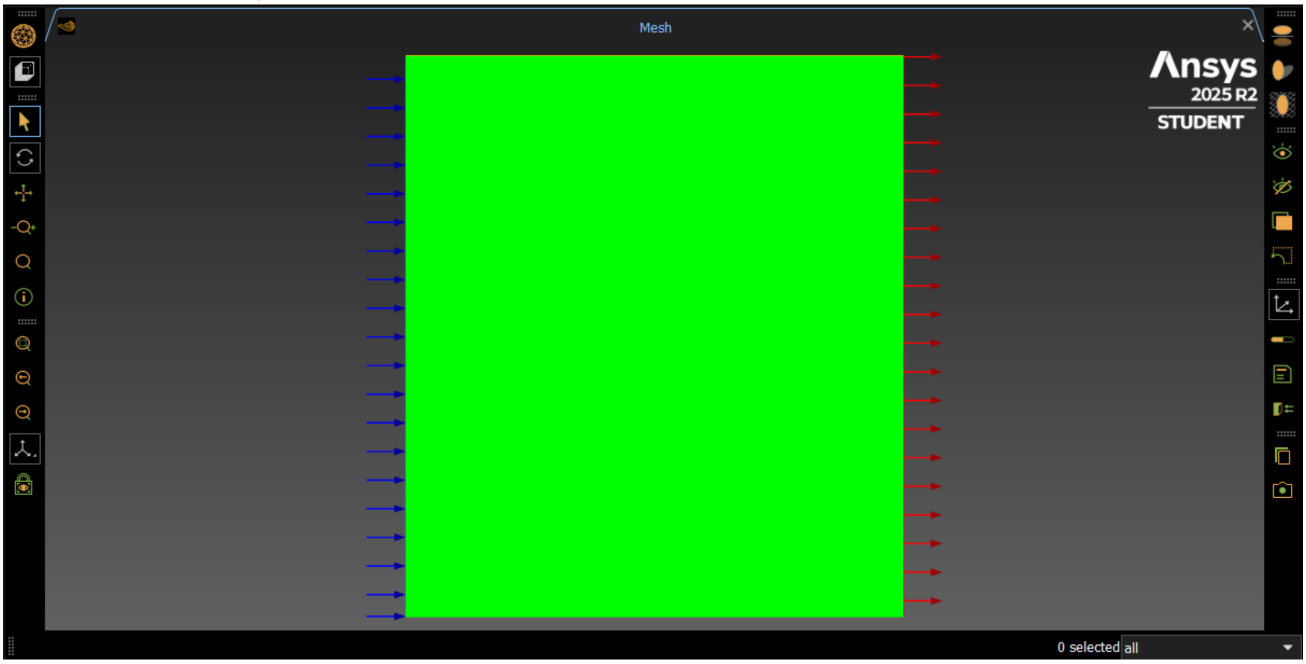

Figure 5: Meshing (ANSYS Fluent)

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

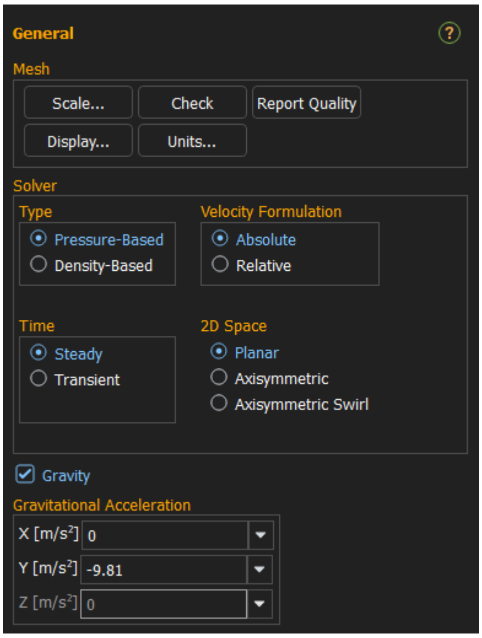

Figure 6: General (ANSYS Fluent)

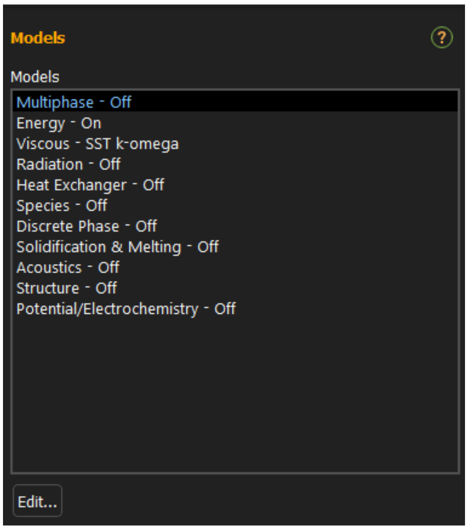

Figure 7: Models (ANSYS Fluent)

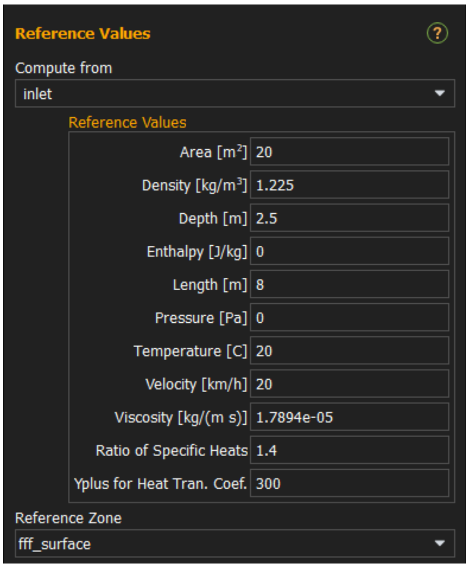

Figure 8: Reference Values (ANSYS Fluent)

Material Properties:

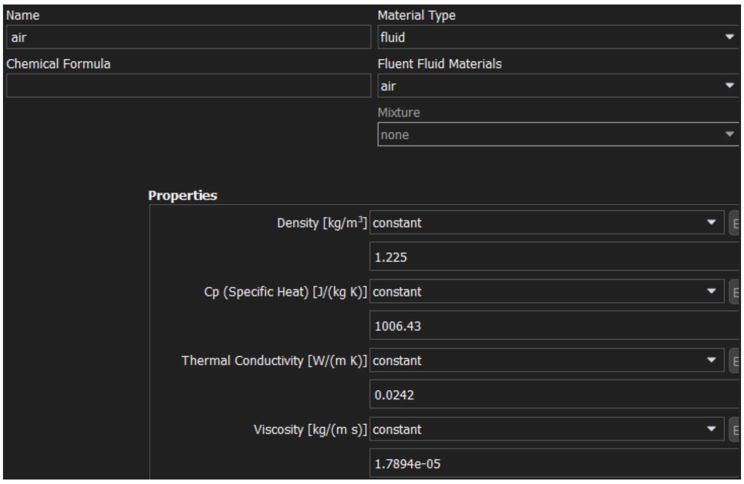

Figure 9.1: Air *(ANSYS Fluent)*

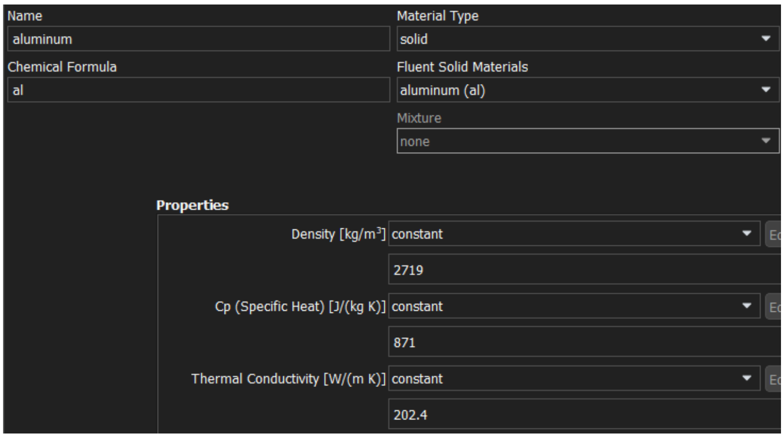

Figure 9.2: Aluminum *(ANSYS Fluent)*

Boundary Conditions:

i. Inlet:

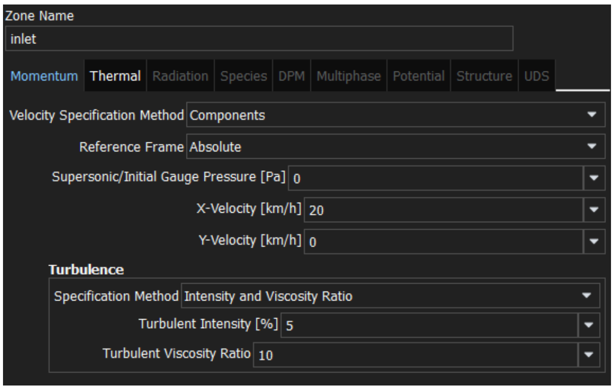

Figure 10.1: Inlet (Momentum) *(ANSYS Fluent)*

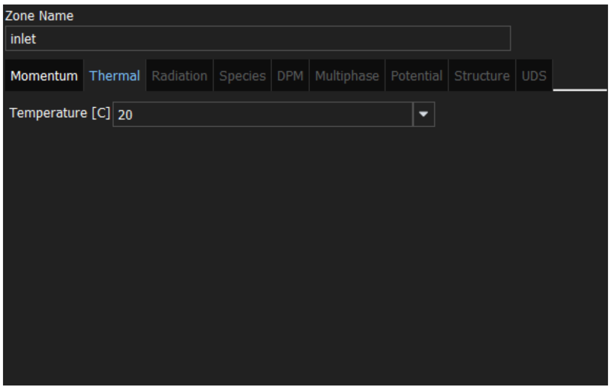

Figure 10.2: Inlet (Thermal) *(ANSYS Fluent)*

ii. Truck Cartage Plate:

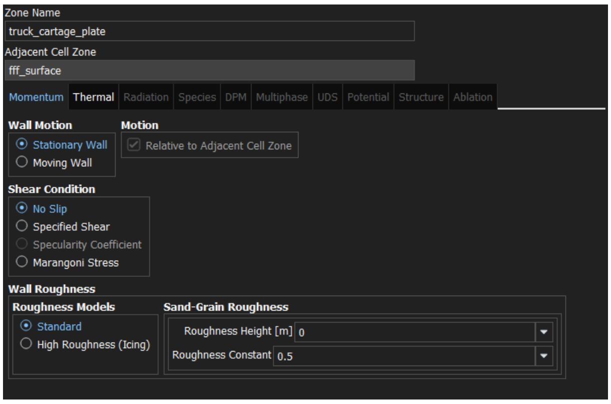

Figure 11.1: Plate (Momentum) *(ANSYS Fluent)*

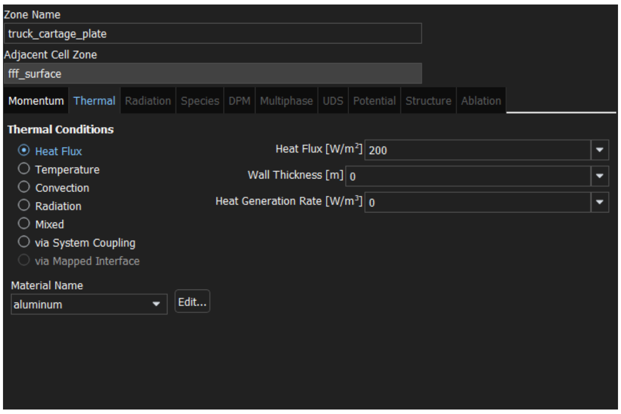

Figure 11.2: Plate (Thermal) *(ANSYS Fluent)*

iii. Top Boundary:

- The top boundary is defined as Symmetry, so it doesn't interfere with the plate.

iv. Outlet:

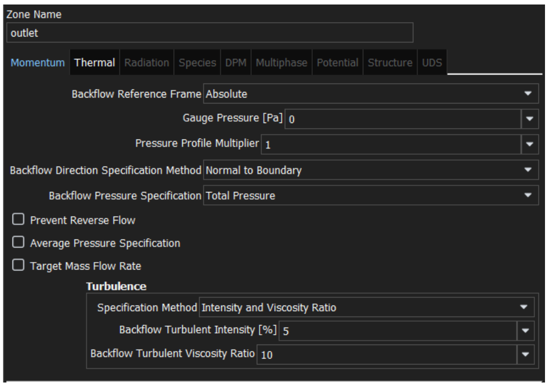

Figure 12.1: Outlet (Momentum) *(ANSYS Fluent)*

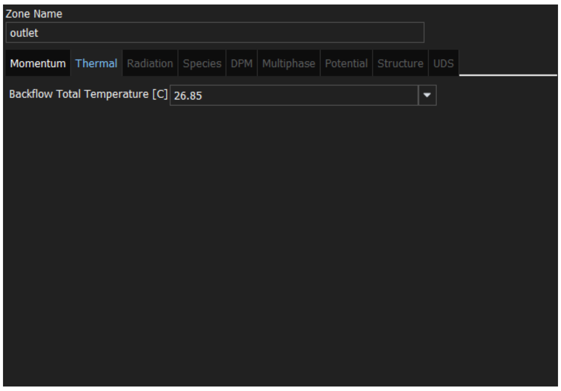

Figure 12.2: Outlet (Thermal) *(ANSYS Fluent)*

Report Definitions:

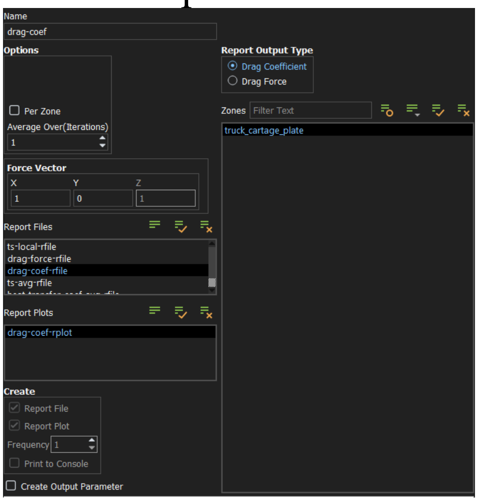

Figure 13.1: Drag Coefficient *(ANSYS Fluent)*

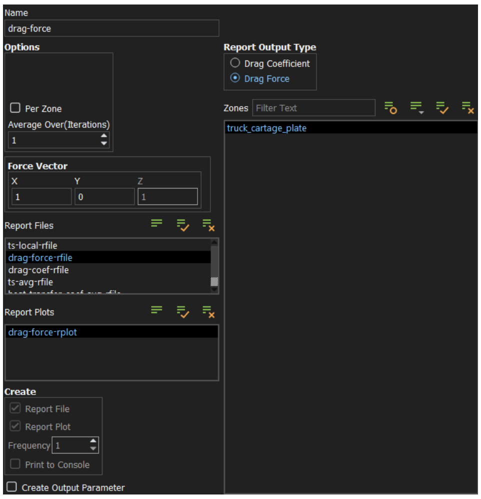

Figure 13.2: Drag Force *(ANSYS Fluent)*

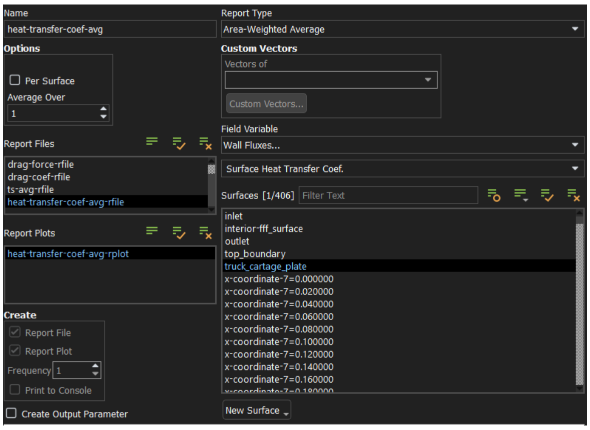

Figure 13.3: Average Heat Transfer Coefficient *(ANSYS Fluent)*

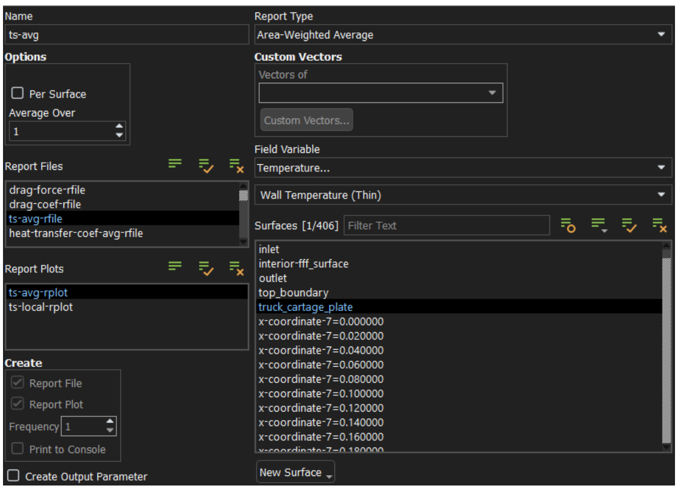

Figure 13.4: Average Temperature *(ANSYS Fluent)*

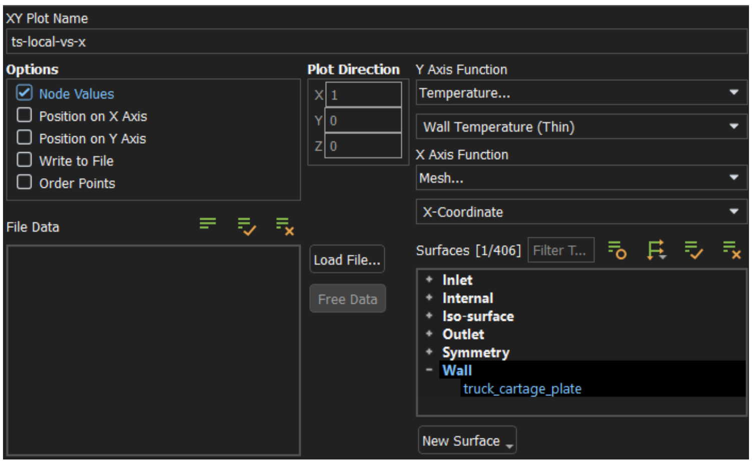

Figure 13.5: Local Temperature *(ANSYS Fluent)*

Calculation Settings:

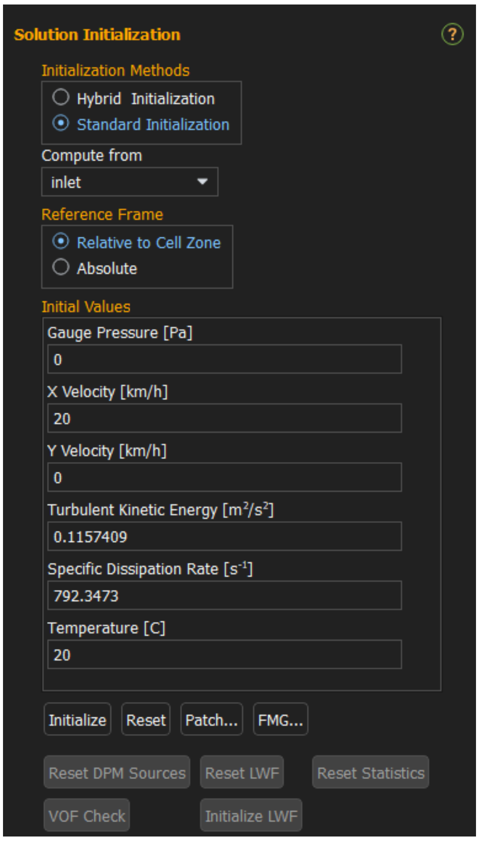

Figure 14.1: Initialization *(ANSYS Fluent)*

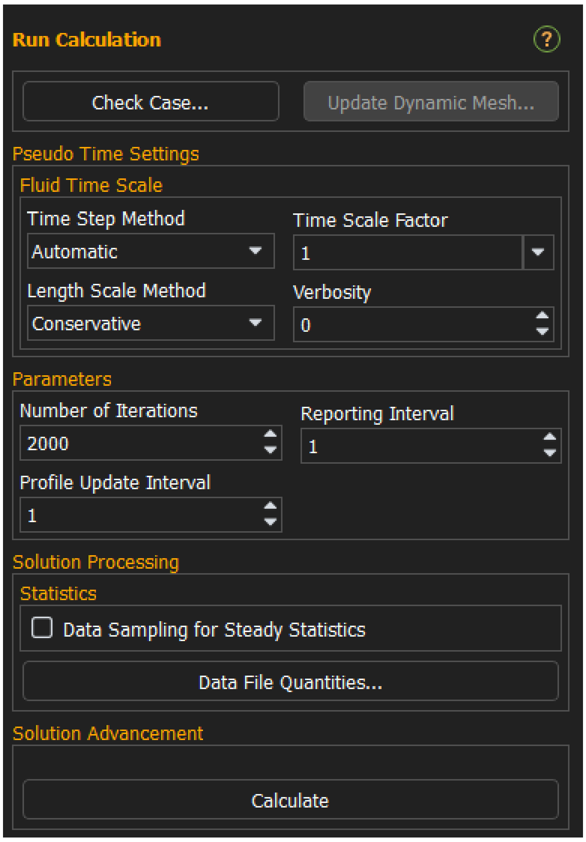

Figure 14.2: Run Calculation *(ANSYS Fluent)*

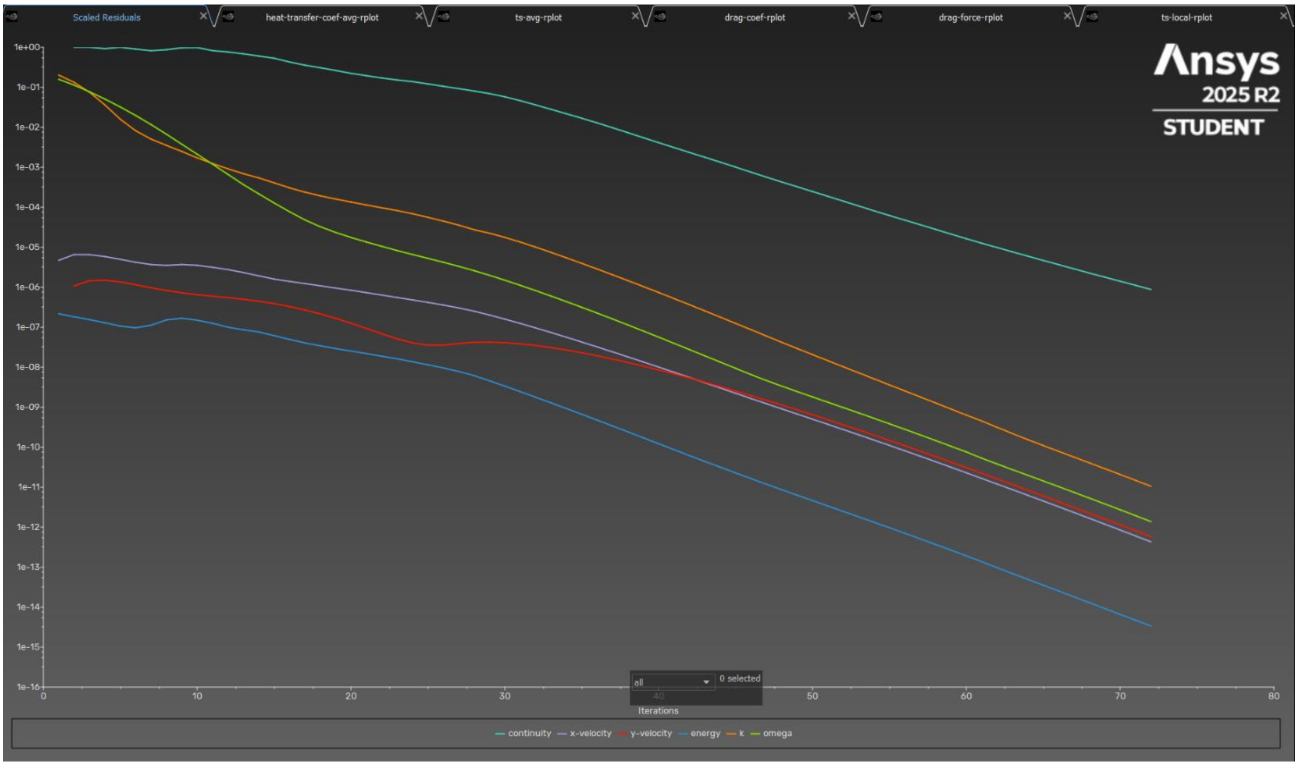

Figure 14.3: Scaled Residuals Curve *(ANSYS Fluent)*

NUMERICAL RESULTS

Coarse Mesh (Element Size: 0.10 m):

- Solutions converged after an average of 118 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	25.0912811	23.2166712	22.4225447	21.9706195	21.6754191	21.4645180	21.3052982
1	31.0327210	26.4149445	24.6021708	23.6242273	23.0066348	22.5801606	22.2673456
2	33.0520976	27.4591041	25.3099995	24.1652331	23.4471383	22.9525813	22.5896962
3	35.1472059	28.5405149	26.0008457	24.6625215	23.8326091	23.2656692	22.8523899
4	37.2807260	29.7025084	26.7726226	25.2338123	24.2843424	23.6395826	23.1709258
5	39.0298036	30.7714118	27.5446593	25.8378762	24.7793617	24.0568458	23.5307997
6	40.4009702	31.5709142	28.1153789	26.2847927	25.1487933	24.3730296	23.8081042
7	41.5589614	32.2354375	28.5856066	26.6504125	25.4491723	24.6287713	24.0313259
8	42.5658261	32.8076337	28.9864180	26.9595958	25.7015600	24.8426384	24.2173346

Figure 15.1: Ts vs x Table (Excel)

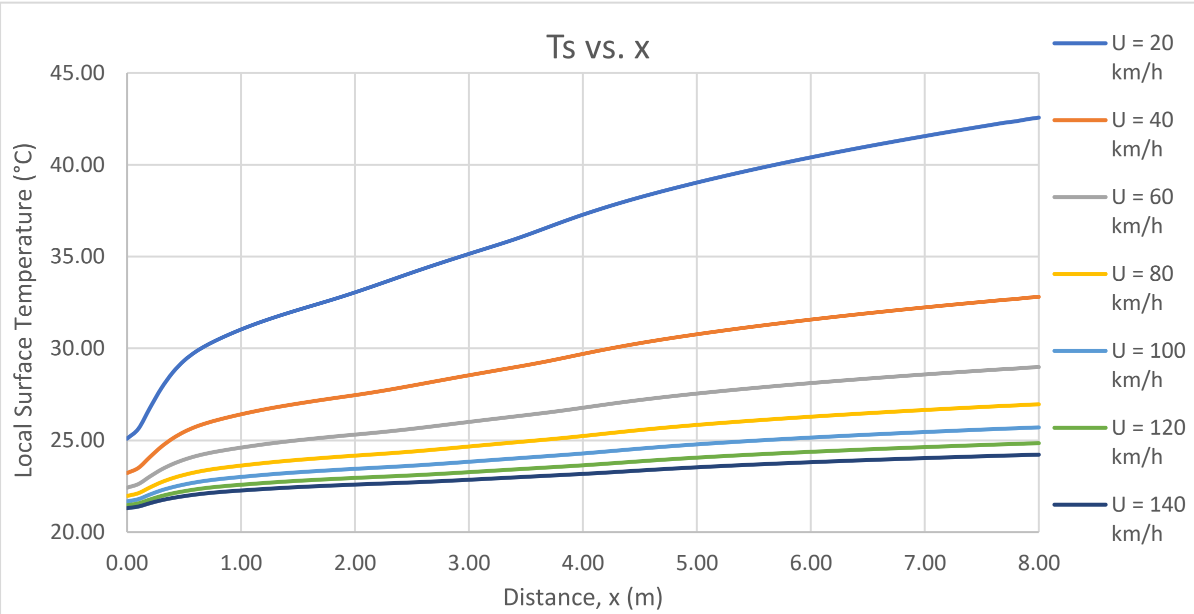

Figure 15.2: Requirement [1] (Excel)

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	36.518	13.390	1.0919	0.0028880
40	29.391	23.317	3.9372	0.0026033
60	26.615	32.835	8.4146	0.0024729
80	25.143	42.011	14.4480	0.0023884
100	24.226	50.922	21.9870	0.0023261
120	23.599	59.609	30.9880	0.0022766
140	23.142	68.117	41.4220	0.0022358

Figure 15.3: Requirement Results (Excel)

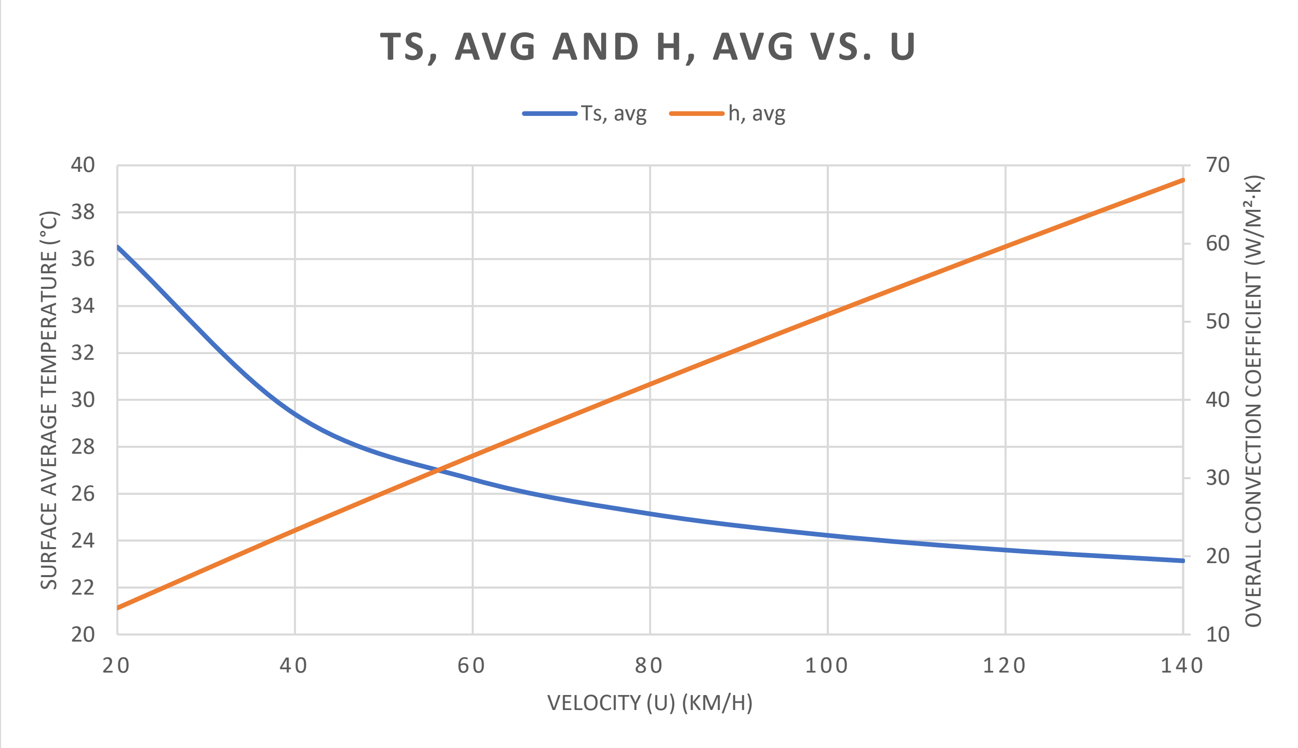

Figure 15.4: Requirement [2] *(Excel)*

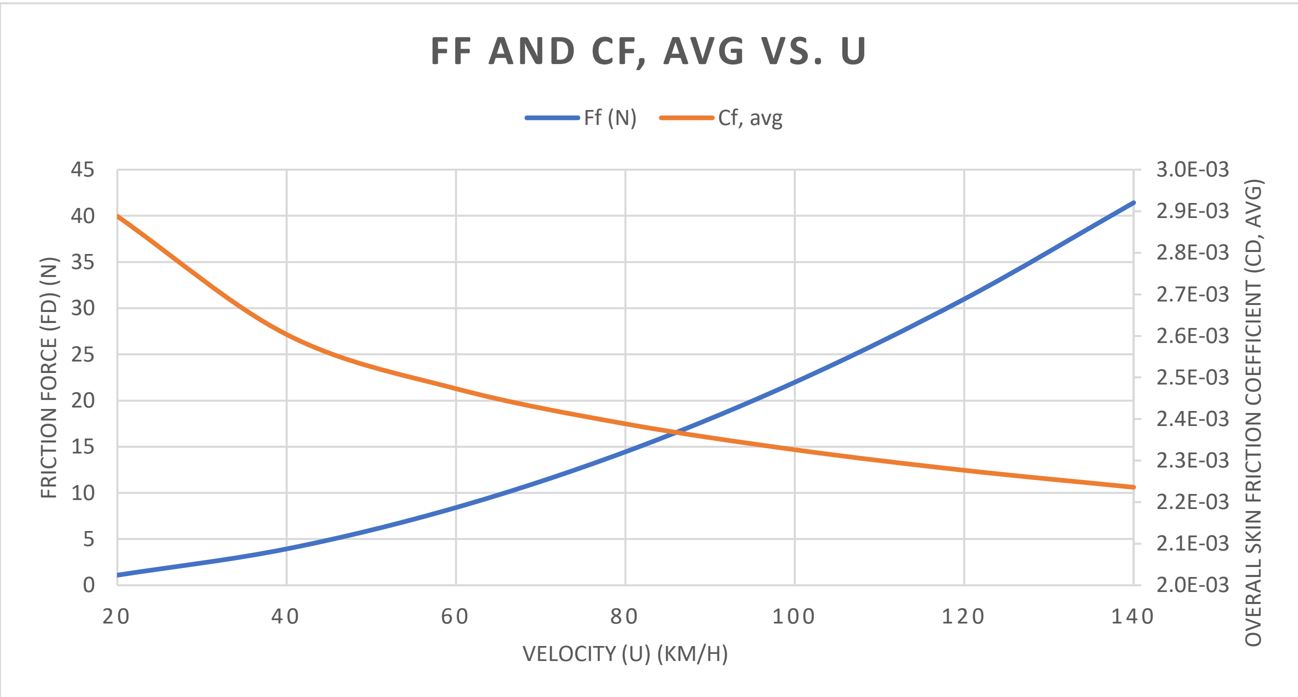

Figure 15.5: Requirement [3] *(Excel)*

Medium Mesh (Element Size: 0.05 m):

- Solutions converged after an average of 115 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	23.7247303	22.5427064	21.9552815	21.6069241	21.3762518	21.2100322	21.0837889
1	30.7169454	26.4140237	24.6820976	23.7035534	23.0784666	22.6435275	22.3222631
2	33.6612812	27.7555348	25.5733288	24.3588138	23.5917700	23.0637072	22.6775338
3	36.4392708	29.3338351	26.7141335	25.2416178	24.3060305	23.6608884	23.1891486
4	38.2994815	30.4252807	27.5161624	25.8817082	24.8386025	24.1175292	23.5894183
5	39.6392289	31.2336739	28.1013929	26.3462244	25.2235577	24.4466995	23.8774187
6	40.4238590	31.8140161	28.5383330	26.6998230	25.5197472	24.7013996	24.1008958
7	40.5762836	32.1361508	28.8196608	26.9377850	25.7251501	24.8820819	24.2622999
8	40.6162836	32.1297270	28.9069865	27.0426782	25.8310431	24.9833167	24.3571676

Figure 16.1: Ts vs x Table (Excel)

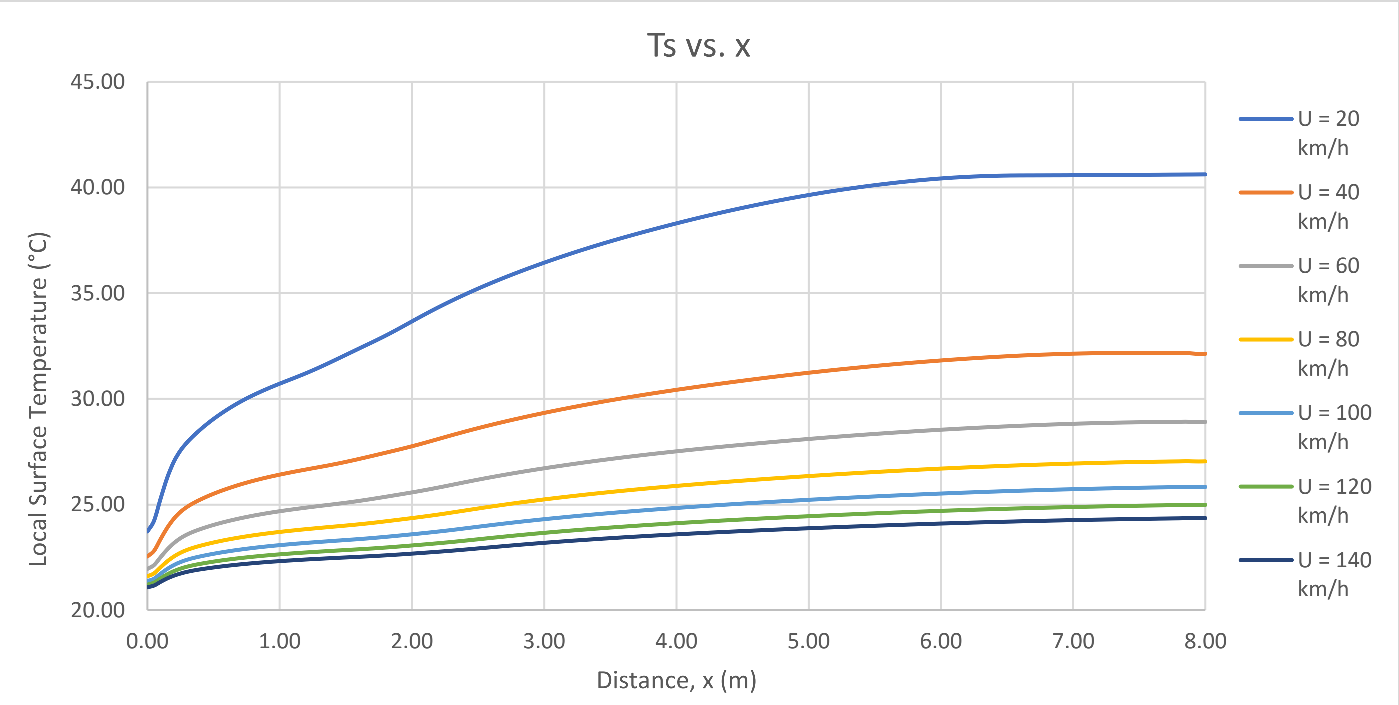

Figure 16.2: Requirement [1] (Excel)

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	36.641	13.348	1.0882	0.0028782
40	29.661	22.733	3.7461	0.002477
60	26.993	31.315	7.8969	0.0023207
80	25.49	39.765	13.5020	0.002232
100	24.529	48.060	20.5160	0.0021705
120	23.863	56.206	28.9030	0.0021235
140	23.373	64.220	38.6370	0.0020855

Figure 16.3: Requirement Results (Excel)

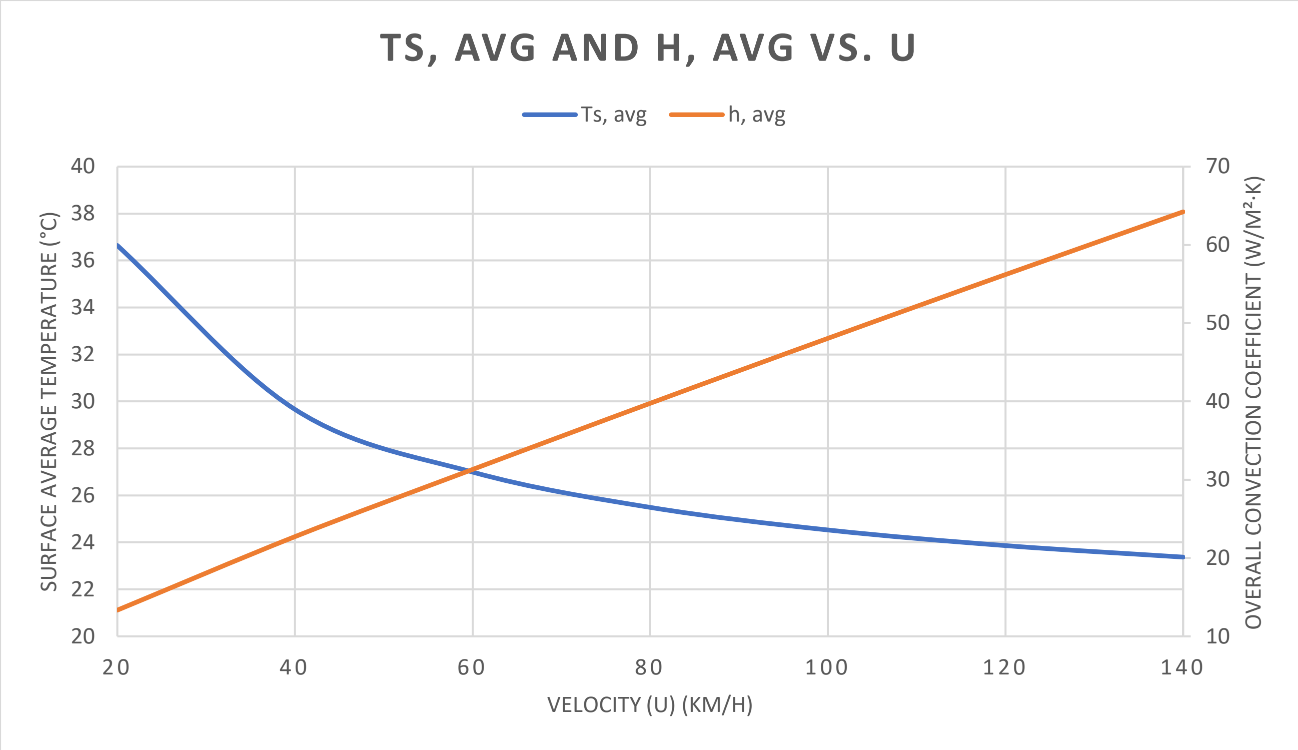

Figure 16.4: Requirement [2] (Excel)

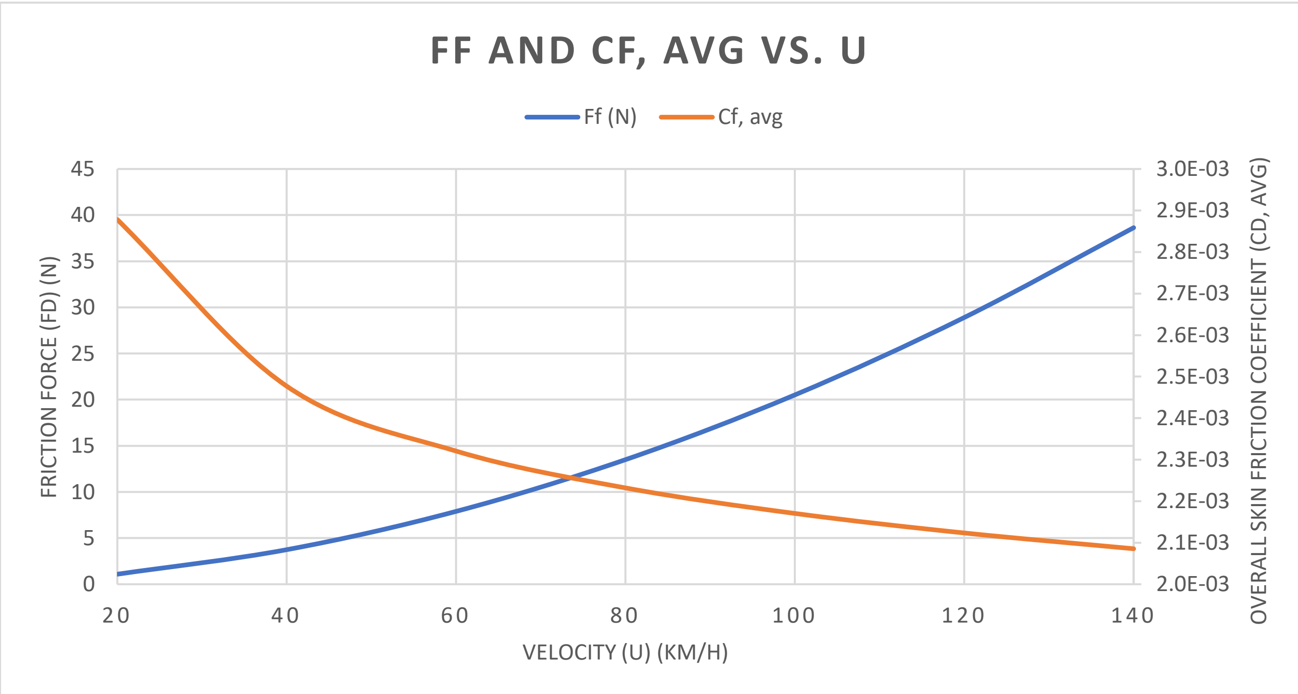

Figure 16.5: Requirement [3] (Excel)

Fine Mesh (Element Size: 0.02 m):

- Solutions converged after an average of 76 iterations.
- To avoid non-physical temperature dips associated with an abrupt laminar–turbulent transition, the boundary layer over the truck roof was assumed to undergo a smooth transition (effectively fully turbulent), which is representative of external vehicle flows at high Reynolds numbers and yields a physically monotonic surface temperature distribution.

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	22.4659462	21.7707896	21.4416384	21.2174503	21.0582913	20.9397281	20.8478200
1	31.4720894	26.4283554	24.6208626	23.7063223	23.1078079	22.6766857	22.3533707
2	35.5559440	28.5825970	26.1781556	24.8821186	24.0870302	23.5164027	23.0851017
3	36.5081256	29.4781844	26.9528585	25.5118798	24.6253290	23.9914578	23.5094142
4	36.5081256	29.4850140	27.0150573	25.6066833	24.7321429	24.1019264	23.6201071
5	36.5754689	29.4850140	27.0150573	25.6066833	24.7321429	24.1019264	23.6201071
6	37.3107312	29.6245147	27.0150573	25.6066833	24.7321429	24.1019264	23.6201071
7	37.9778681	30.0122665	27.2526982	25.7090428	24.7817127	24.1207496	23.6201071
8	38.4315442	30.2939312	27.5008171	25.9068157	24.9444517	24.2579762	23.7364088

Figure 17.1: Ts vs x Table *(Excel)*

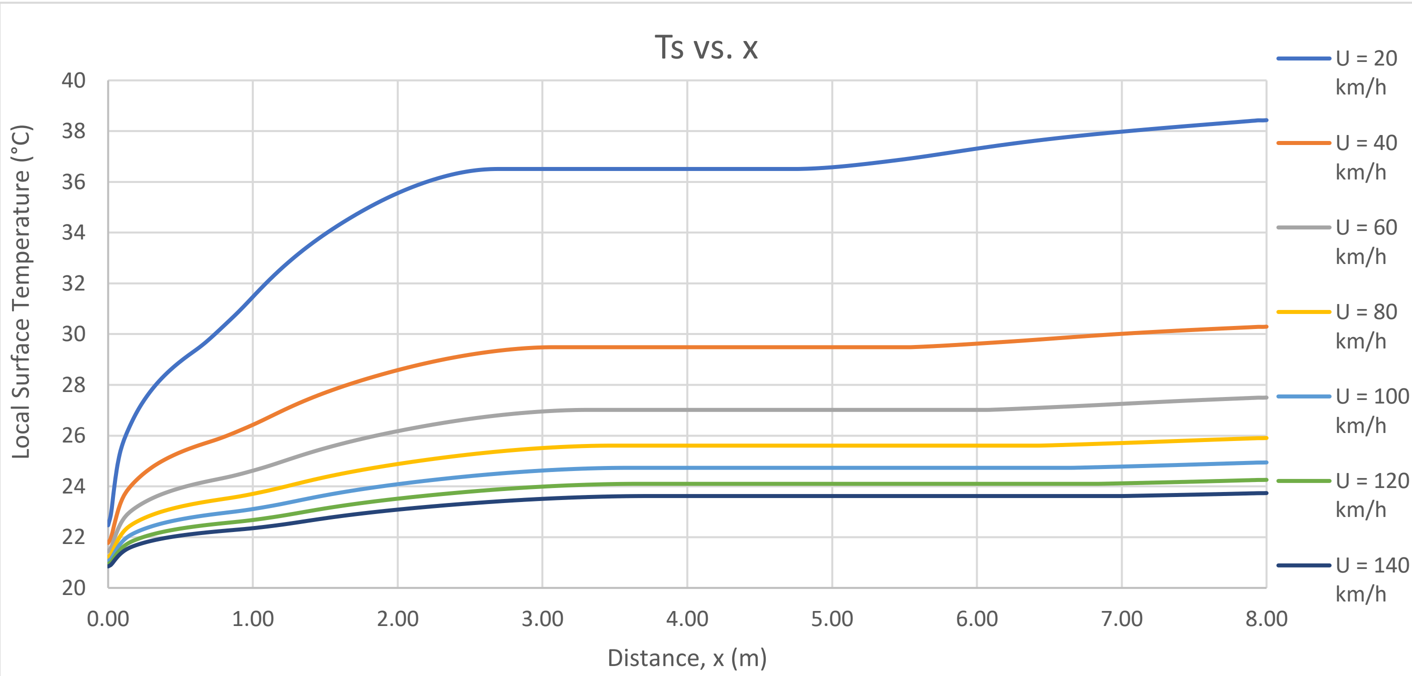

Figure 17.2: Requirement [1] *(Excel)*

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	34.768	14.456	1.2501	0.0033063
40	28.359	25.244	4.3365	0.0028674
60	26.103	34.483	8.8743	0.0026079
80	24.876	43.035	14.8670	0.0024575
100	24.104	51.106	22.3180	0.0023612
120	23.547	59.115	31.2050	0.0022926
140	23.124	67.083	41.4980	0.00224

Figure 17.3: Requirement Results (Excel)

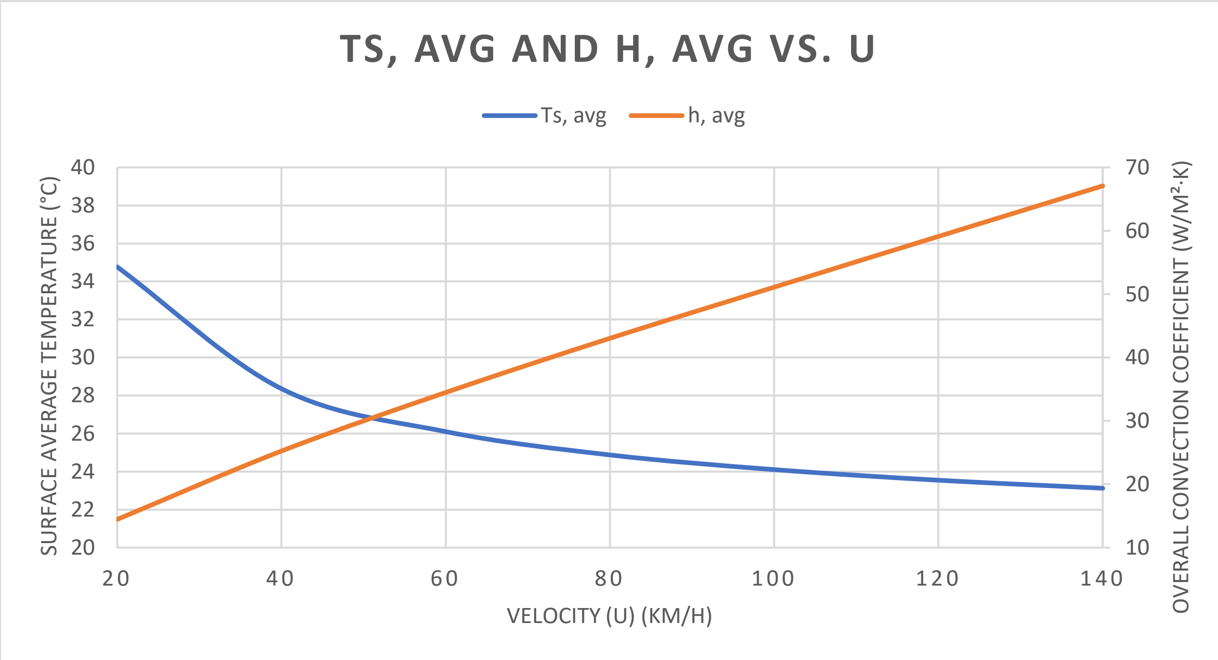

Figure 17.4: Requirement [2] (Excel)

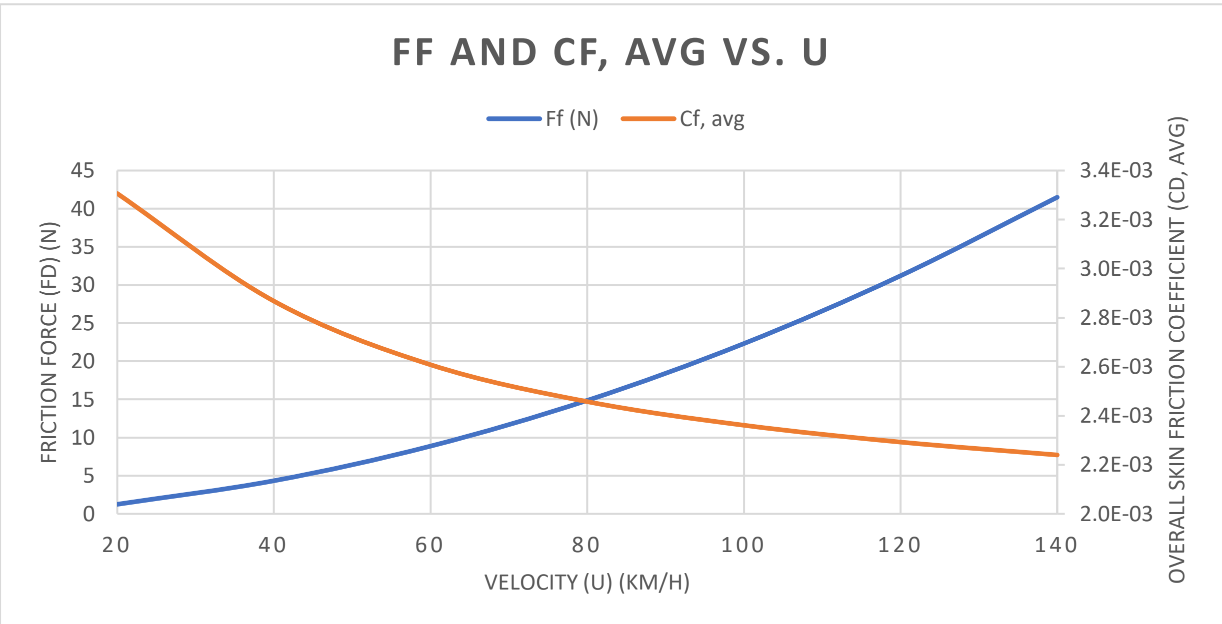

Figure 17.5: Requirement [3] (Excel)

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	25.143	42.011	14.4480	0.0023884
Medium	25.49	39.765	13.5020	0.002232
Fine	24.876	43.035	14.8670	0.0024575

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	(25.143 – 24.876) / 24.876 = **1.07%**	(42.011 – 43.035) / 43.035 = **2.38%**	(14.448 – 14.867) / 14.867 = **2.82%**	(0.0023884 – 0.0024575) / 0.0024575 = **2.81%**
Medium → Fine deviation:	(25.49 – 24.876) / 24.876 = **2.47%**	(39.765 – 43.035) / 43.035 = **7.60%**	(13.502 – 14.867) / 14.867 = **9.18%**	(0.002232 – 0.0024575) / 0.0024575 = **9.18%**

Figure 18.2: Numerical Deviation (Excel)

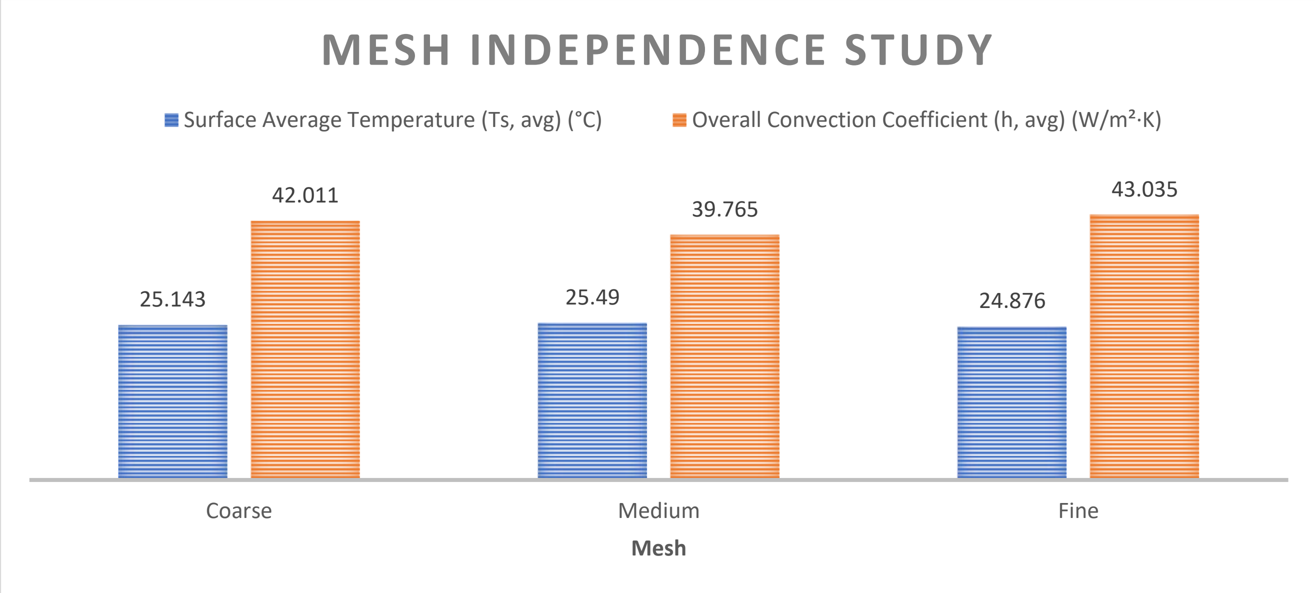

Figure 18.3: Mesh Independence Study Graph (Excel)

Interpretation of Results:

The comparison between mesh levels shows that the **Coarse mesh exhibits the largest deviations** when compared to the Fine mesh, with differences of approximately **1–3%** in surface temperature, heat transfer coefficient, friction force, and skin-friction coefficient. These deviations indicate that the Coarse mesh does not sufficiently resolve the near-wall boundary layer, leading to less reliable thermal and aerodynamic predictions.

The **Medium mesh**, while improving over the Coarse mesh, still shows **noticeable deviations relative to the Fine mesh**, particularly in the convection coefficient and friction-related quantities, where deviations reach up to **7–9%**. This suggests that the Medium mesh has not yet reached mesh-independent behavior for quantities strongly influenced by boundary-layer resolution.

The **Fine mesh** provides the most reliable solution, yielding the **smoothest and most physically consistent temperature distribution along the plate**, especially near the leading edge where thermal and velocity gradients are steep. Accurate resolution in this region is critical for heat-transfer-dominated analyses.

Based on these observations, the **Fine mesh is selected for all final simulations**, as it ensures adequate boundary-layer resolution and minimizes numerical discretization errors, thereby providing the highest confidence in the reported results.

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 $G = 1000\ \text{W/m}^2$, 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 $q'' = 200\ \text{W/m}^2$.
- A blended correlation was used to ensure smooth transition between laminar and turbulent regimes.

MATLAB Code:

- 1st Requirement

```
Empirical Heat Transfer on Truck Roof (MATLAB)
clc; clear; close all;
%% ---------------- Geometry & constants -------------------
L = 8;                     % Plate length (m)
W = 2.5;                   % Plate width (m)
G = 1000;                  % Solar irradiation (W/m^2)
alpha = 0.2;
q_abs = alpha * G;         % Absorbed heat flux (W/m^2)
T_inf = 293;               % Ambient temperature (K)
% Air properties (assumed constant)
rho = 1.2;                 % kg/m^3
mu  = 1.8e-5;              % Pa.s
k   = 0.026;               % W/m.K
Pr  = 0.71;
Re_crit = 5e5;             % Critical Reynolds number
%% ---------------- Discretization -------------------------
dx = 0.02;                 % Spatial step (m)
x  = 0:dx:L;               % Distance along plate (m)
x_eff = max(x,0.01);       % Avoid singularity at x = 0
U_kmh = 20:20:140;         % Velocity sweep (km/h)
U = U_kmh / 3.6;           % Convert to m/s
%% ---------------- Preallocate ----------------------------
Ts = zeros(length(U), length(x));    % Surface temperature (°C)
%% ---------------- Main calculation ------------------------
for j = 1:length(U)
    Re_x = rho * U(j) .* x_eff / mu;
    % Laminar and turbulent Nusselt numbers
    Nu_lam = 0.332 .* Re_x.^0.5 .* Pr^(1/3);
    Nu_tur = 0.0296 .* Re_x.^0.8 .* Pr^(1/3);
    % Strict regime selection
Nu_lam = 0.332 .* Re_x.^0.5 .* Pr^(1/3);
Nu_tur = 0.0296 .* Re_x.^0.8 .* Pr^(1/3);
Nu_x = sqrt(Nu_lam.^2 + Nu_tur.^2);
   % Heat transfer coefficient
    h_x = Nu_x .* k ./ x_eff;
    % Surface temperature (°C)
    Ts(j,:) = T_inf + q_abs ./ h_x - 273;
end
```

EES Code:

- 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	22.9447344	21.8475701	21.3933441	21.1360707	20.9676787	20.8477138	20.7573238
1	29.9386574	25.7616697	24.1820730	23.3299267	22.7897826	22.4138301	22.1355896
2	31.5233394	26.6598534	24.8276601	23.8410284	23.2163316	22.7818620	22.4604969
3	32.5462189	27.2414902	25.2463461	24.1727930	23.4933812	23.0210118	22.6716979
4	33.3197069	27.6820568	25.5637240	24.4243948	23.7035527	23.2024730	22.8319797
5	33.9489132	28.0408290	25.8223021	24.6294409	23.8748675	23.3504061	22.9626609
6	34.4829804	28.3455860	26.0420237	24.8037095	24.0204873	23.4761634	23.0737608
7	34.9491275	28.6117393	26.2339617	24.9559645	24.1477252	23.5860543	23.1708490
8	35.3641136	28.8487896	26.4049459	25.0916139	24.2610949	23.6839732	23.2573638

Figure 19.1: Ts vs x Table (Matlab)

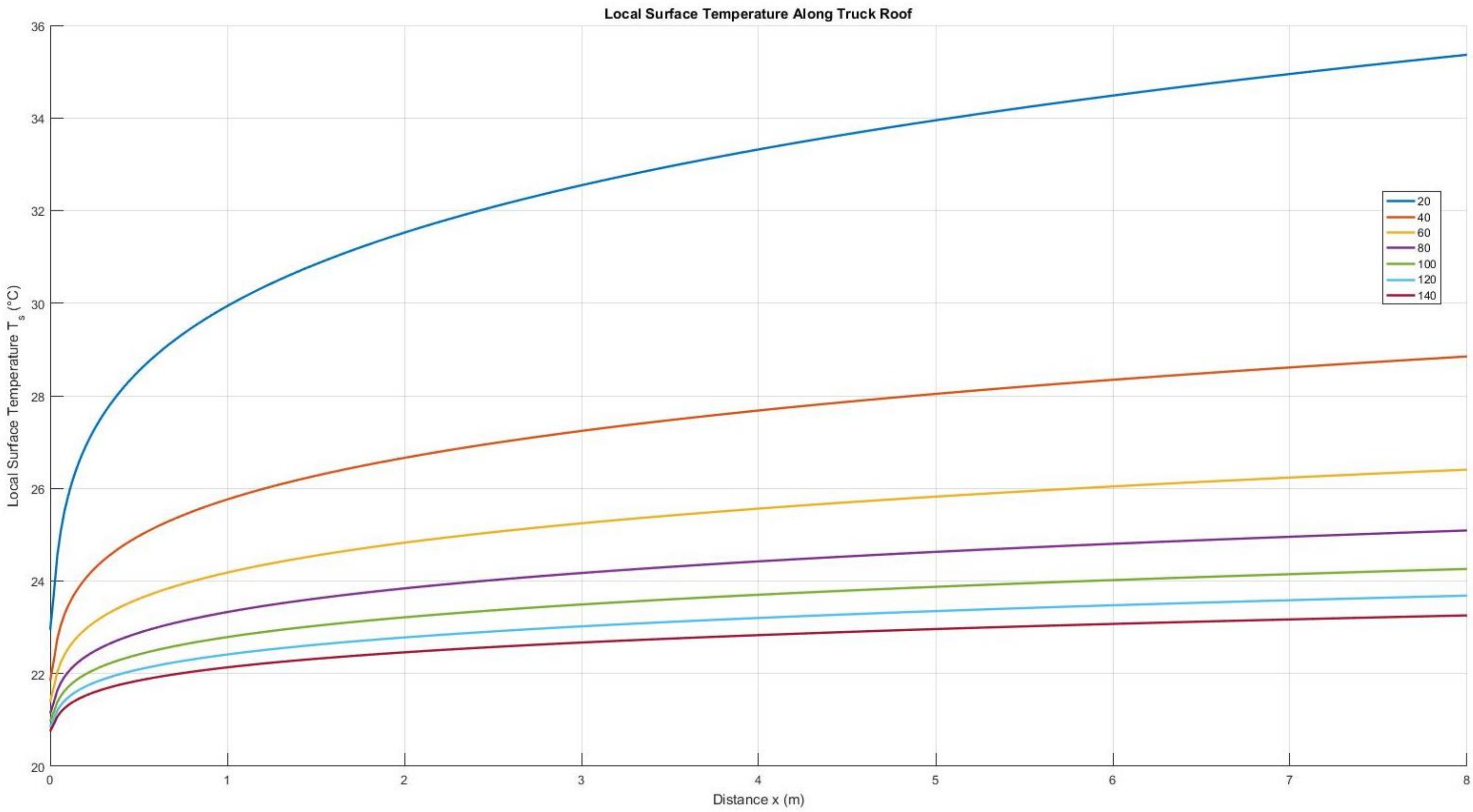

Figure 19.2: Ts vs x Curve (Matlab)

- 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)

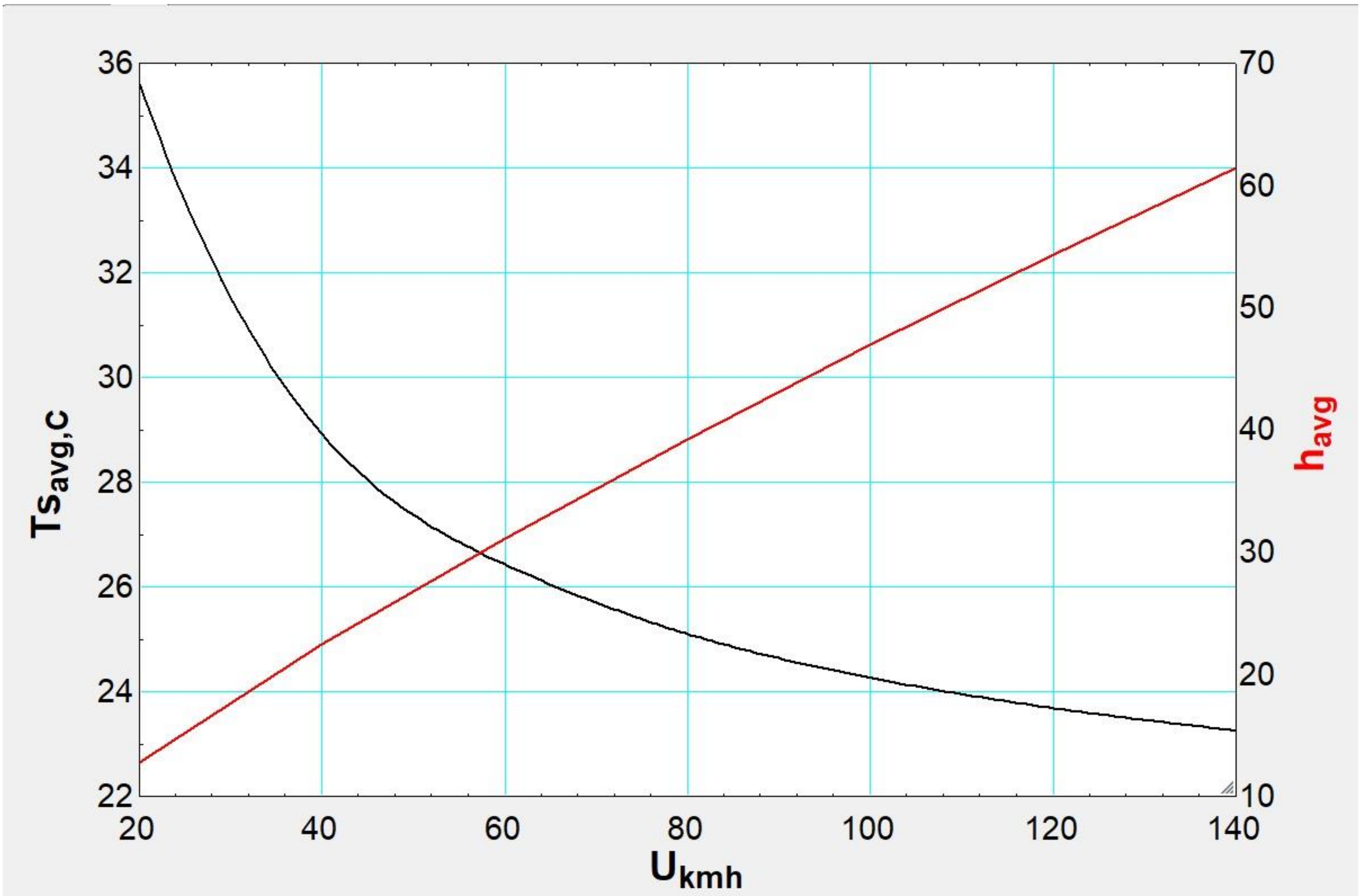

Figure 20.2: Ts, avg and h, avg Vs U Curve (EES)

- 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)

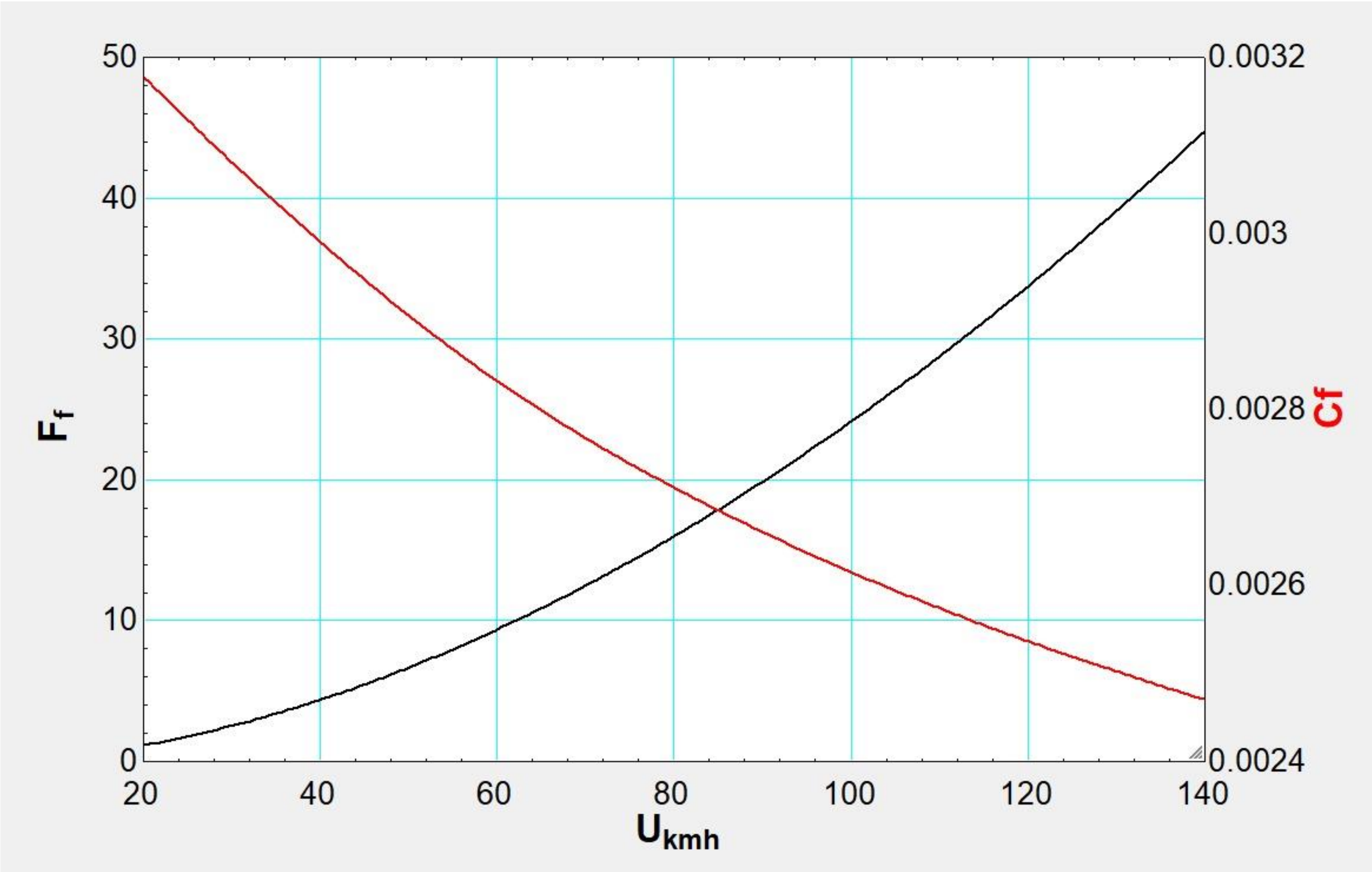

Figure 21.2: Fd and Cd, avg Vs U Curve (EES)

NUMERICAL VS. EMPIRICAL COMPARISON

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

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 **0.819 °C**, while the mean signed error (MSE) was **+0.819 °C**, indicating a consistent overall **over-prediction** by the numerical model. The mean absolute percentage error (MAPE) was **3.36%**, confirming good agreement between the CFD results and the empirical flat-plate correlations.

x (m)	Ts (Numerical)	Ts (Empirical)	Absolute Error (°C)	% Error
0	21.2174503	21.1360707	0.0813796	0.39%
1	23.7063223	23.3299267	0.3763956	1.61%
2	24.8821186	23.8410284	1.0410902	4.37%
3	25.5118798	24.1727930	1.3390868	5.54%
4	25.6066833	24.4243948	1.1822885	4.84%
5	25.6066833	24.6294409	0.9772424	3.97%
6	25.6066833	24.8037095	0.8029738	3.24%
7	25.7090428	24.9559645	0.7530783	3.02%
8	25.9068157	25.0916139	0.8152018	3.25%

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

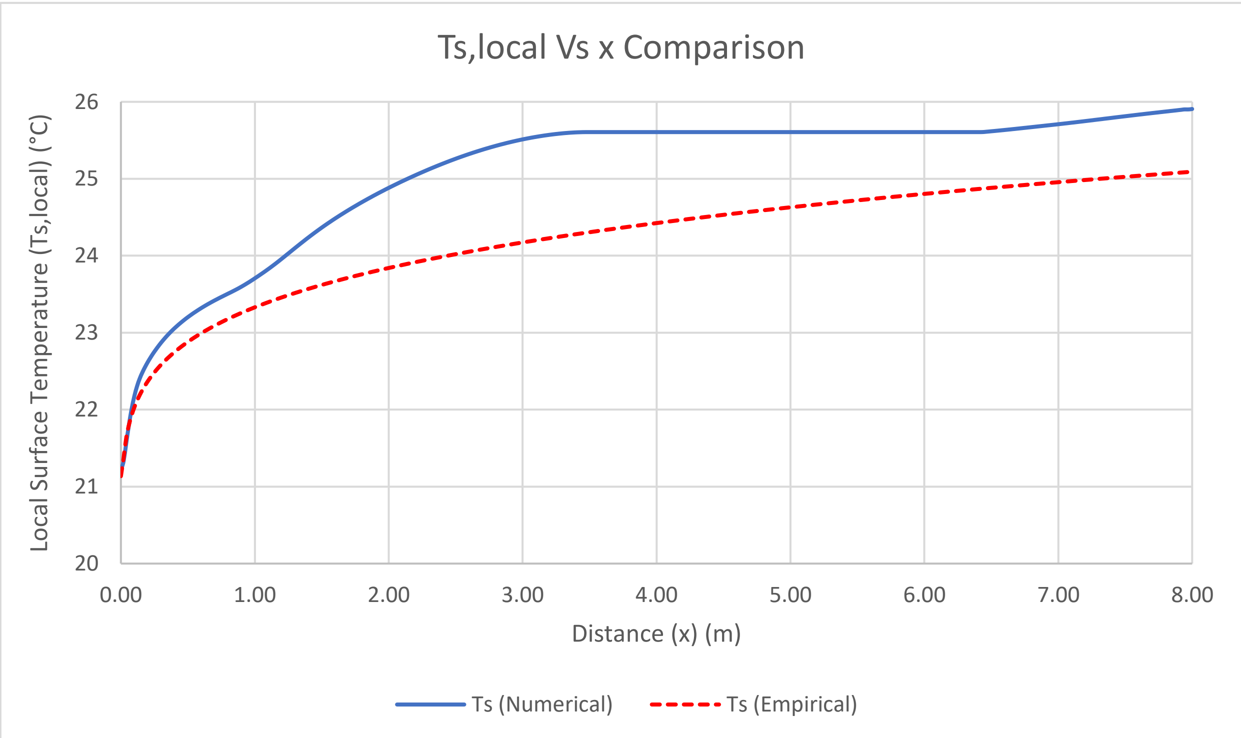

Figure 22.2: Ts, local Vs. x Comparison Curve (Excel)

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 **0.24 °C** and a mean signed error (MSE) of **−0.24 °C**, indicating a small and consistent under-prediction relative to the empirical correlations. The mean absolute percentage error (MAPE) was **0.80%**, demonstrating **excellent agreement** between the numerical and empirical results across the investigated velocity range.
- In contrast, the average convection coefficient showed a higher level of deviation, with an MAE of **4.18 W/m²·K** and a MAPE of **11.49%**. The numerical model consistently over-predicted the heat transfer coefficient, which can be attributed to idealized flow assumptions and the enhanced near-wall resolution achieved in the CFD simulation compared to classical flat-plate empirical 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	34.768	35.49	0.722	2.03%	14.456	12.79	1.666	13.03%
40	28.359	28.83	0.471	1.63%	25.244	22.27	2.974	13.35%
60	26.103	26.34	0.237	0.90%	34.483	30.8	3.683	11.96%
80	24.876	25.01	0.134	0.54%	43.035	38.77	4.265	11.00%
100	24.104	24.16	0.056	0.23%	51.106	46.35	4.756	10.26%
120	23.547	23.58	0.033	0.14%	59.115	53.63	5.485	10.23%
140	23.124	23.15	0.026	0.11%	67.083	60.67	6.413	10.57%

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

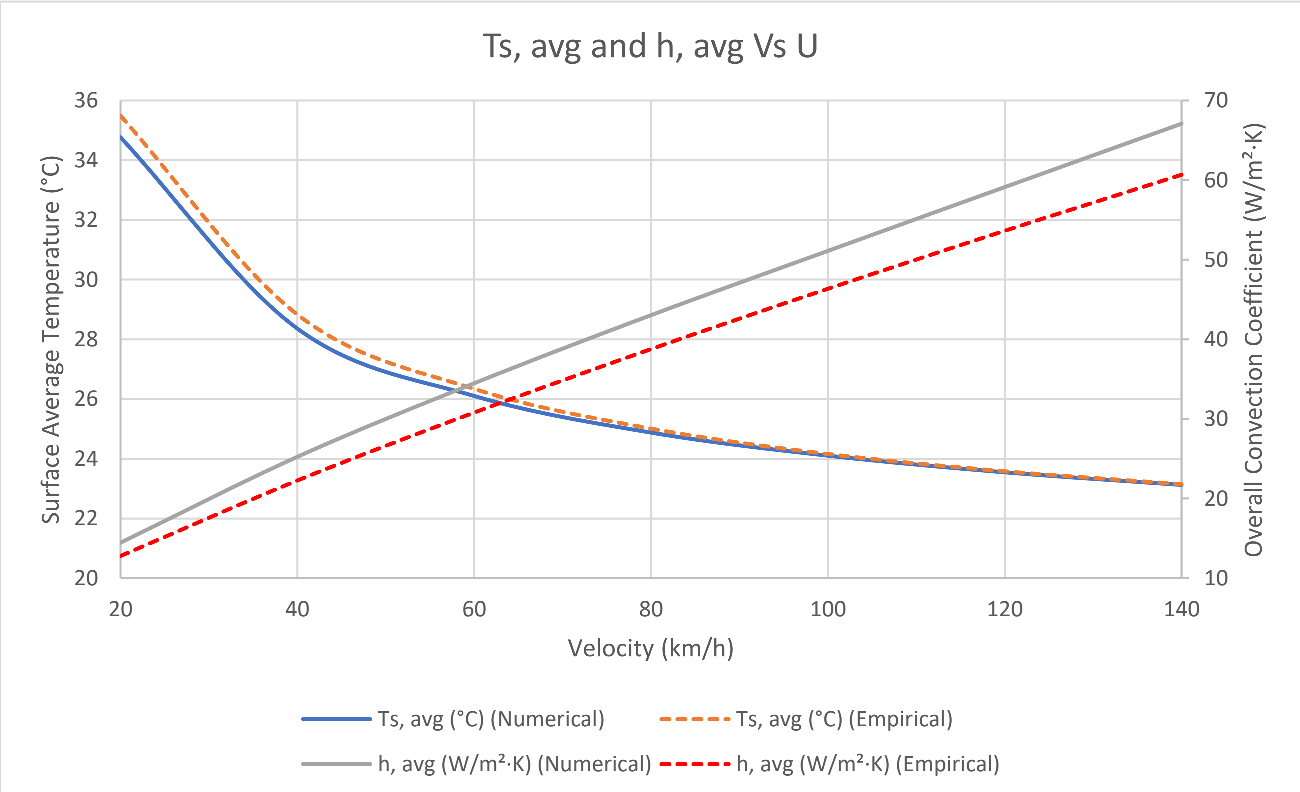

Figure 23.2: Ts, avg and h, avg Vs. U Comparison Curve (Excel)

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 **1.93 N** and a mean absolute percentage error (MAPE) of **9.84%** over the investigated velocity range. The negative mean signed error indicates a systematic under-prediction of drag force relative to empirical correlations, which is commonly observed in CFD simulations due to idealized surface smoothness and the absence of surface roughness effects present in experimental correlations.
- The average skin friction coefficient exhibited moderate deviations from empirical values, yielding a MAPE of **13.83%** and a mean absolute error of approximately **4.15×10^{-4}**. Despite this under-prediction, the numerical results capture the correct physical trend with velocity, confirming that the CFD model adequately represents wall shear behavior, while highlighting the sensitivity of skin-friction predictions to near-wall modeling assumptions.

Velocity (U) (km/h)	Fd (N) (Numerical)	Fd (N) (Empirical)	Absolute Error (N)	% Error	Cd, avg (Numerical)	Cd, avg (Empirical)	Absolute Error	% Error
20	1.2501	1.374	0.1239	9.02%	0.0033063	0.003803	0.0004967	13.06%
40	4.3365	4.785	0.4485	9.37%	0.0028674	0.00331	0.0004426	13.37%
60	8.8743	9.927	1.0527	10.60%	0.0026079	0.003052	0.0004441	14.55%
80	14.8670	16.66	1.793	10.76%	0.0024575	0.002882	0.0004245	14.73%
100	22.3180	24.9	2.582	10.37%	0.0023612	0.002756	0.0003948	14.33%
120	31.2050	34.57	3.365	9.73%	0.0022926	0.002657	0.0003644	13.71%
140	41.4980	45.62	4.122	9.04%	0.00224	0.002577	0.0003370	13.08%

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

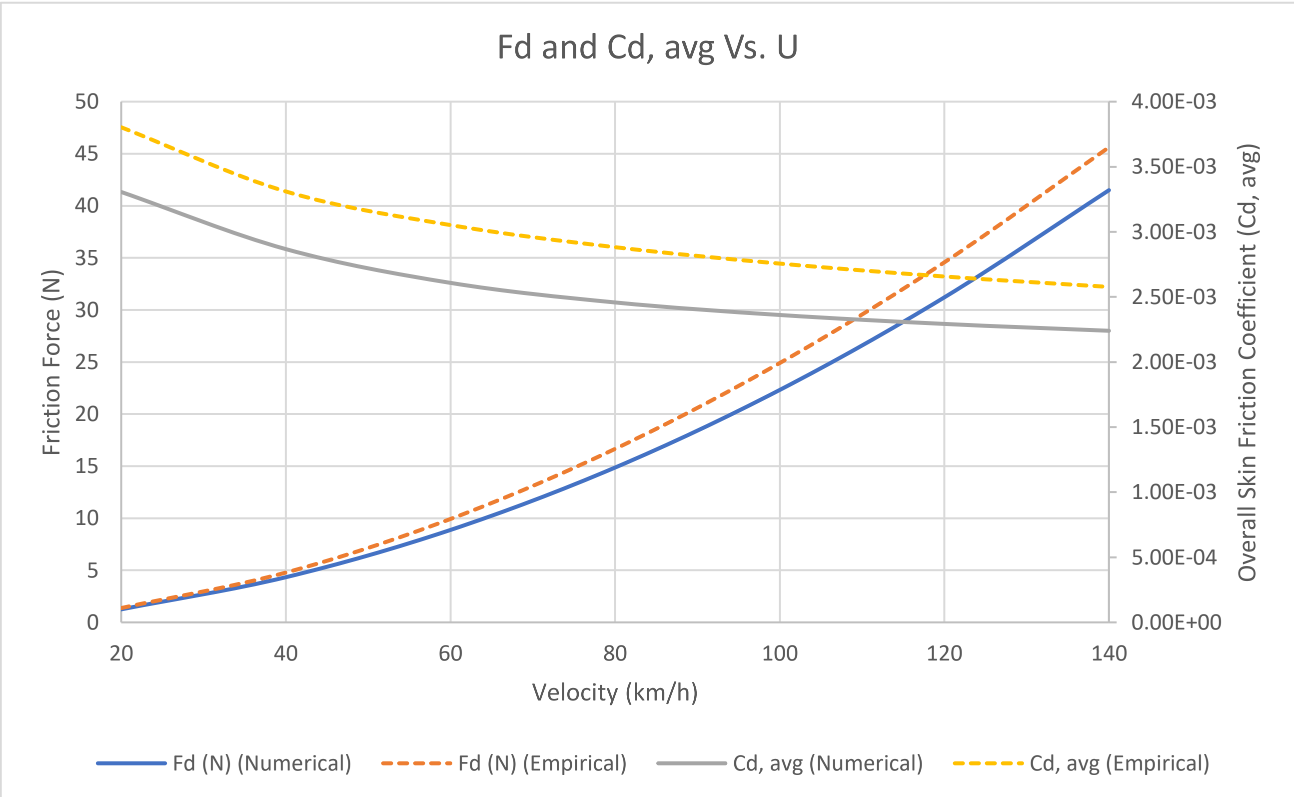

Figure 24.2: Fd and Cd, avg Vs. U Comparison Curve (Excel)

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 small discrepancies, with a mean absolute percentage error (MAPE) of approximately **3.36%**, 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 **0.80%**. The convection coefficient exhibited larger deviations (≈**11.5%**), 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 good agreement with empirical correlations, yielding a MAPE of **9.84%** for friction force and **13.83%** 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.