Aerodynamic Flow Model Tester

Governing Equations, Browser Numerical Methods, Validation Strategy, and Interpretive Limits

Tool route	/rc/afmt/
Version	1.0.0
Primary use	Interactive comparison of uploaded STL models and preset aerodynamic test geometries
Modes	Analytical Preview and coarse browser Numerical Solve
Geometry privacy	Uploaded STL files remain in browser memory and are not transmitted by the application

Scope statement

The Aerodynamic Flow Model Tester is a research and education interface for rapid visualization, comparative testing, and preliminary aerodynamic reasoning. Its analytical fields are interpretive approximations. Its numerical mode is a deliberately coarse D3Q19 lattice-Boltzmann calculation designed for browser execution. Neither mode is represented as certification-grade computational fluid dynamics or as a substitute for calibrated wind-tunnel measurements.

Supported model classes

Version one provides selectable aircraft, automobile, building, and drone/projectile categories. Each category includes a local test STL. The same upload pipeline accepts user-provided ASCII or binary STL geometry.

Why boundary-layer profiles appear for buildings

Wind speed close to the ground is not uniform. Buildings experience vertical shear that depends on surface roughness and surrounding terrain. The urban, suburban, and open-country inlet profiles are therefore relevant to architectural wind loading and wake interpretation. Uniform inlet flow remains available for controlled comparison and for non-building tests.

Prepared for Stella Nova Research Center. Equations are expressed in SI units unless otherwise stated.

1. Coordinates, Geometry, and Reference Quantities

The model x-axis is treated as the nominal streamwise direction. The y-axis is lateral and the z-axis is vertical. Yaw, pitch, roll, and angle of attack rotate the model relative to the freestream. Uploaded STL scale is dimensionless until a known physical length is supplied.

Reference length and areas

```
L = selected characteristic length
```

```
A_ref = projected frontal area for drag; S_ref = planform/reference area for lift
```

The browser derives normalized triangle bounds, surface area, enclosed signed volume, and projected-area proxies from the model mesh. For arbitrary non-manifold STL files, volume may be unreliable; the interface therefore emphasizes projected areas and displays mesh diagnostics.

Blockage ratio

```
beta = A_model,max / A_tunnel
```

Blockage estimates how strongly tunnel walls may accelerate the flow around a model. A bounded virtual tunnel should be interpreted cautiously as beta grows. The interface reports the ratio but does not apply a universal wall-interference correction because correction procedures depend on tunnel configuration, model type, and flow regime.

Ground conditions

Mode	Interpretation
Open-air / far-field	Side and upper boundaries are treated as distant; no ground interaction is imposed.
Bounded wind tunnel	Side boundaries represent a finite test section.
Rolling-road ground plane	The ground moves with freestream speed, reducing artificial underbody boundary-layer growth for vehicle studies.
Stationary ground plane	A no-slip ground is conceptually represented for buildings and stationary objects.

2. Atmospheric State

Moist-air density

```
rho = p_d / (R_d T) + p_v / (R_v T)
```

Here p_d is dry-air partial pressure, p_v is water-vapor partial pressure, R_d = 287.058 J/(kg K), R_v = 461.495 J/(kg K), and T is absolute temperature. Relative humidity controls p_v through saturation vapor pressure. This implementation is an engineering approximation informed by the CIPM moist-air formulation; it is not a full metrology implementation of every CIPM correction term.

Standard-atmosphere pressure approximation

```
p = p0 (1 - 2.25577e-5 h)^5.25588        for h <= 11,000 m
p = 22632.06 exp[-g (h - 11000)/(R_d 216.65)]  above 11,000 m
```

When Custom pressure is selected, the entered pressure is retained. Otherwise altitude updates atmospheric pressure using the piecewise approximation above.

Dynamic viscosity: Sutherland relation

```
mu = 1.458e-6 T^(3/2) / (T + 110.4)
```

The Sutherland relation provides a practical estimate for air viscosity over the intended temperature range. Humidity has a much smaller effect on viscosity than on density and is not separately modeled in version one.

Speed of sound

```
a = sqrt(gamma R_d T),       gamma = 1.4
```

Mach number uses this local speed-of-sound estimate.

3. Similarity and Aerodynamic Coefficients

Reynolds number

```
Re = rho U L / mu
```

Reynolds number measures the ratio of inertial to viscous effects and is essential when comparing a model-scale test with a full-scale configuration.

Mach number

```
M = U / a
```

The standard version targets low-speed and moderately compressible conditions from 0 to 150 m/s. The interface warns conceptually above M = 0.3 because density variation and compressibility corrections become increasingly important.

Dynamic pressure

```
q = 0.5 rho U^2
```

Force and moment coefficients

```
C_D = D / (q A_ref)
C_L = L / (q S_ref)
C_Y = Y / (q A_ref)
C_m = M_pitch / (q S_ref L)
```

Coefficients normalize forces and moments so that configurations can be compared across changes in speed, density, and physical scale, provided relevant similarity parameters are also considered.

Power associated with drag

```
P_D = D U
```

This is the instantaneous mechanical power needed to overcome the reported aerodynamic drag at the selected speed. It does not include propulsion-system efficiency, installation losses, or vehicle accessory loads.

4. Analytical Preview

Analytical Preview is designed to remain responsive during model rotation and parameter changes. It uses model-class priors, projected-area measures, Reynolds and Mach scaling, angle-of-attack terms, side-slip terms, and roughness/turbulence modifiers. The resulting coefficients are comparative estimates rather than a resolved solution of the Navier-Stokes equations.

Representative lift approximation

```
C_L = a_alpha alpha cos(beta)
```

The lift-curve slope a_alpha varies by preset class. Stall is represented only by a soft attenuation at high absolute angle of attack; the interface does not predict detailed stall onset, buffet, or dynamic hysteresis.

Representative drag polar

```
C_D = C_D0 + C_L^2 / (pi e AR) + C_alpha sin^2(alpha) + C_beta sin^2(beta)
```

The analytical model combines a baseline drag term, an induced-drag proxy, and orientation penalties. The values are intended to make directionally correct A/B comparisons within the same category, not to recover an aircraft or vehicle certification polar.

Surface pressure visualization

```
C_p = (p - p_inf) / q
```

Triangle colors are generated from local surface normal, streamwise position, angle of attack, and model category. They indicate likely stagnation, suction, and recovery regions. They are not cell-resolved pressure data unless the numerical overlay is active.

Wake and vorticity visualization

Animated streamlines bend around an influence volume derived from the normalized model bounds. Aircraft presets add paired wingtip-vortex spirals. Buildings increase lateral and vertical displacement. Wake opacity scales with the estimated drag, blockage, and selected turbulence intensity.

5. Browser Numerical Solve

Numerical Solve uses a Web Worker so the interface remains responsive. The worker voxelizes the transformed STL into a Cartesian lattice and advances a D3Q19 single-relaxation-time lattice-Boltzmann scheme. This is intentionally coarser than professional CFD meshes.

Lattice-Boltzmann evolution

```
f_i(x + c_i dt, t + dt) = f_i(x,t) - omega [f_i(x,t) - f_i^eq(x,t)]
```

Equilibrium distribution

```
f_i^eq = w_i rho [1 + 3(c_i.u) + 4.5(c_i.u)^2 - 1.5(u.u)]
```

Macroscopic recovery

```
rho = sum_i f_i,        rho u = sum_i f_i c_i
```

The worker applies a velocity inlet, copied-gradient outlet, and bounce-back at voxelized solid cells. Side boundaries are periodic for the open approximation and bounce-back for the bounded-tunnel option.

Effective lattice Reynolds number

To retain stability on small browser grids, the worker caps the effective lattice Reynolds number far below many physical full-scale values. The physical Reynolds number remains visible, while the numerical status reports convergence, residual, grid, and iteration count. This distinction is essential: the numerical field is a coarse flow-structure visualization, not a dynamically similar full-scale solution.

Force modifier

Momentum exchange at obstacle links supplies a lattice drag signal. The signal is used as a bounded modifier to the analytical drag estimate rather than presented as an independently converged engineering force.

6. Category-Specific Interpretation

Category	Primary outputs	Important limitations
Aircraft / wing	Lift, drag, L/D, wingtip-vortex and pressure patterns	No control-surface actuation, propulsion, transition model, shock resolution, or dynamic stall.
Automobile	Drag, underbody/ground comparison, crosswind side force	Wheel rotation is represented only through the rolling-road boundary choice; rotating-wheel flow is
Building	Pressure tendency, wake, crosswind response, atmospheric profile selection	No structural response, pedestrian comfort standard, aeroelasticity, or urban-array interaction in v
Drone / projectile	Drag, orientation sensitivity, wake and vorticity	No rotor momentum source, propeller slipstream, spin stabilization, or high-Mach shock physics.

Atmospheric boundary-layer inlet

```
U(z) = U_ref (z / z_ref)^alpha_p
```

For building studies, a power-law profile is used as a visualization and scaling proxy. The exponent alpha_p is category-dependent: lower over open terrain and higher over dense urban terrain. The selected profile should match the intended exposure, and a uniform profile should be retained when comparing against a uniform-flow wind-tunnel dataset.

Crosswind and yaw

Yaw changes the relative flow direction and produces a side-force proxy. For buildings and vehicles, crosswind can dominate local separation and wake behavior. For aircraft, beta is interpreted as sideslip. The analytical preview does not solve coupled stability derivatives.

7. Validation and Quality-Control Plan

Required numerical checks

Check	Expected practice
Grid sensitivity	Run low, medium, and high resolutions; compare coefficients and wake structure.
Domain sensitivity	Compare far-field and bounded domains and record blockage ratio.
Time / iteration sensitivity	Confirm residual reduction and stable force trend before interpreting the solve.
Geometry integrity	Inspect scale, orientation, normals, open surfaces, and voxelization diagnostics.
Similarity	Compare Reynolds and Mach numbers with the intended physical case.
Benchmark geometry	Use sphere, finite wing, and simple bluff-body presets before relying on arbitrary uploaded geometry.

External validation targets

Future validation should compare the sphere benchmark against accepted drag trends, the finite wing against published low-speed airfoil/wing data, the vehicle preset against a documented generic automotive benchmark, and the building preset against simple prism wind-tunnel data. Validation datasets must be cited with geometry, test-section, Reynolds number, turbulence intensity, and correction procedures.

Uncertainty statement

The interface reports deterministic values but does not yet propagate uncertainty from geometry scale, atmospheric sensors, tunnel corrections, mesh resolution, or model-form error. Users should treat small percentage differences as unresolved unless they persist across resolution and boundary-condition tests.

8. Interpretive Limits and Responsible Use

The tool is appropriate for teaching, rapid comparative reasoning, UI-guided exploration, and preliminary design communication. It should not be used as the sole basis for structural wind loading, flight safety, vehicle certification, ballistic performance, or any decision where failure could harm people or property.

Specific exclusions

Version one does not include free-flight dynamics, moving control surfaces, rotating propellers or wheels, combustion, heat transfer, icing, rain, multiphase flow, aeroelastic deformation, acoustic prediction, transonic shock capture, supersonic expansion, hypersonic chemistry, or automated regulatory compliance.

STL privacy

STL parsing occurs in the browser. The comments endpoint receives only fields deliberately submitted through the Research Community Comments form. The run JSON and browser report are generated locally.

Reproducibility metadata

A saved run records model key/name, category, airspeed, temperature, altitude, humidity, pressure, turbulence, gust amplitude, orientation, surface roughness, tunnel dimensions, ground mode, inlet profile, resolution, output metrics, and available solver residual metadata.

Recommended interpretation sequence

First verify scale and orientation. Second inspect Reynolds, Mach, and blockage. Third compare analytical results across controlled A/B cases. Fourth repeat with multiple numerical resolutions. Fifth compare against an experimental or validated computational reference before drawing engineering conclusions.

9. Core References

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Citation note

The interface deliberately distinguishes its implemented D3Q19 BGK browser worker from professional Reynolds-averaged Navier-Stokes solvers. The Menter reference is included as an important engineering turbulence-model reference and as context for future higher-fidelity backends; AFMT version 1.0.0 does not implement SST k-omega RANS.

Tool citation

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