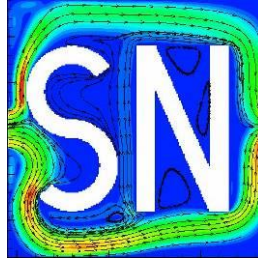


Suction or Blowing on Smooth Flat Plate  
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June 8, 2020

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1.0 Introduction

Suction and blowing of air through localized perforated or porous walls can be used to delay loss of lift (stalling) as the angle of attack of a wing or airfoil is increased . Owing to the lack of suitable experimental data for wings or airfoils, this boundary option was tested using experimental data from turbulent flow over flat plates.

2.0 Turbulent Flow over Flat Plate with Suction

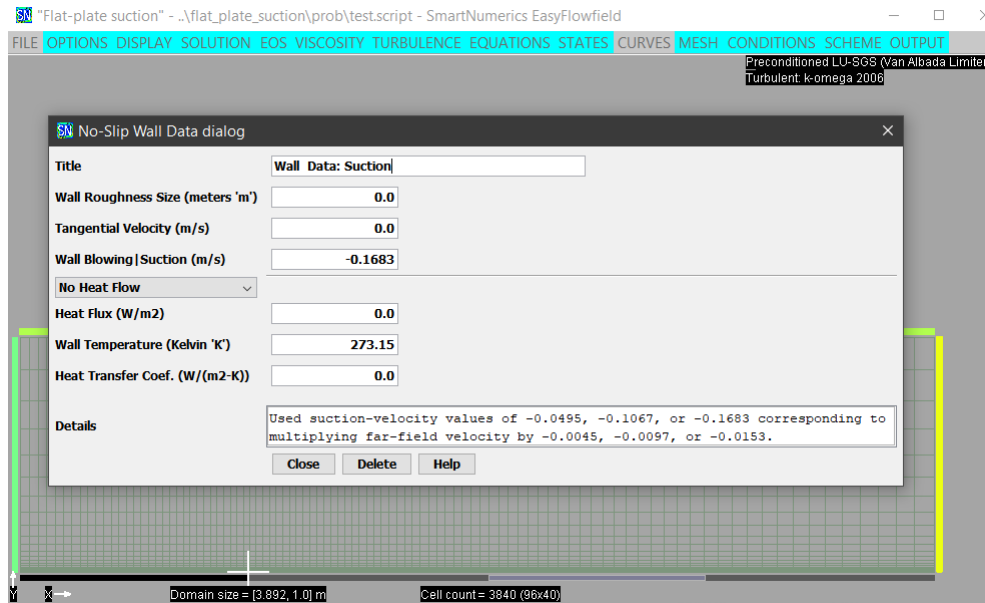


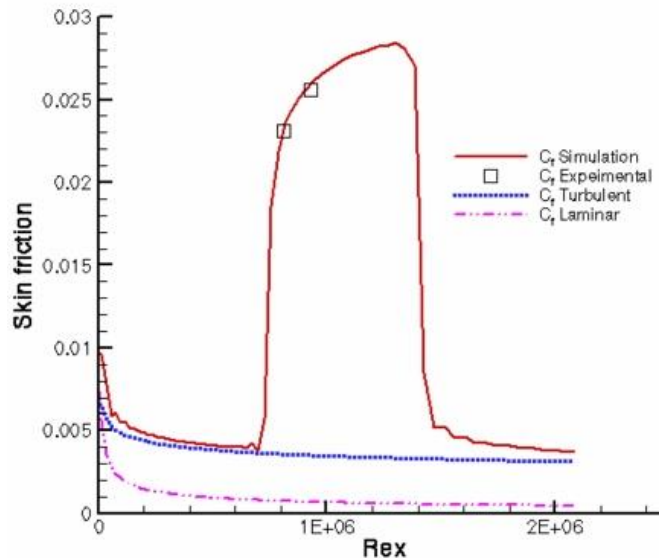
Fig. 1: Grid and no-slip wall data for simulation of flow over plate with suction.

This validation test case is based on the experimental measurements of Favre, Dumas, and Verollet [1] in a wind tunnel with an inflow turbulence intensity of 0.12%. Air with a freestream velocity of 11 m/s flows over a smooth flat plate 1.946 m in length. A perforated section starts 1.026 meters upstream of the leading edge and has a length of 0.92 meters. The plate is perforated with holes that vary in size from a few microns to 100 microns. The percentage of the surface that is solid is about 50%. The Reynolds number based on a boundary layer thickness of 22.5 mm at the start of the porous section is 16,300. The Reynolds number based on the length of 1.026 metres is thus 743,280.

Figure 1 displays the grid and dialog used to input the section velocity which, in this case, was set to -0.0153 times the far-field velocity. An inflow condition with fixed total pressure and total temperature was imposed on the left and an outflow condition with specified static pressure was imposed on the right. A far-field condition was imposed at the top of the grid. At the bottom of the grid, a slip condition (black) is imposed upstream of the plate which is modelled using no-slip boundaries (grey). The light grey area is the region of suction. There was no transfer of heat to the walls (adiabatic).

Favre, Dumas, and Verollet [1], measured values friction with suction, at two locations downstream of the leading edge of the suction plate. The first location was 4.15 times the boundary layer thickness and the second was at 11.5 times the boundary layer thickness.

Using the boundary layer thickness at the suction plate leading edge, these locations are approximately 93 mm and 259 mm downstream of the leading edge of the suction plate, respectively. These locations are thus approximately 1119 mm and 1295 mm downstream of the flat plate leading edge, respectively. The Reynolds numbers based on these distances downstream of the flat plate leading edge are 810,653 and 930,911, respectively.



**Fig. 2: Friction along wall for turbulent flow over flat plate with suction.**

Figure 2 displays friction as a function of

$$Re_x = \frac{\rho_\infty u_\infty x}{\mu_\infty}$$

which is the Reynolds number a specified distance  $x$  downstream of the leading edge of the plate, where  $\mu_\infty$  is the far-field molecular viscosity,  $u_\infty$  is the far-field velocity, and  $\rho_\infty$  is the far-field density. The friction from the simulation is computed using

$$c_f = 2 \frac{\rho_w (u^*)^2}{\rho_\infty U_\infty^2}$$

using the local friction velocity,  $u^*$ , output by the solver. Here,  $\rho_w$  is the density at the wall. The friction from the simulation approaches the friction correlation

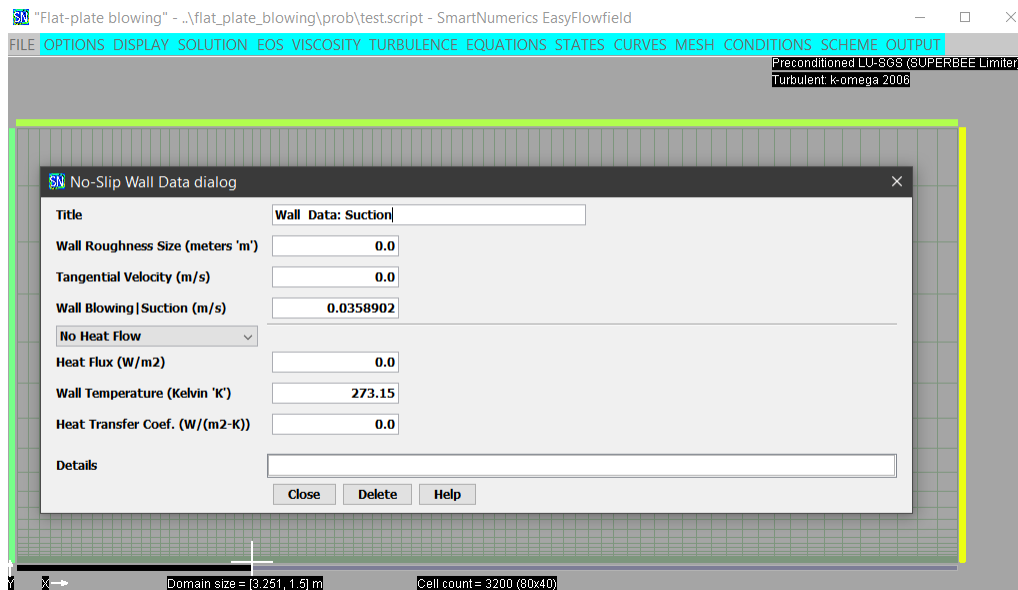
$$c_{f \text{ Turbulent}} = .025 (\text{Re}_x)^{-1/7}$$

for fully turbulent flow on a solid wall until the suction plate is reached where the friction quickly rises and produces a good fit to the two experimental values. The friction from the simulation continues to rise until the end of the suction plate is reached where the friction drops rapidly. The friction remains well above the Blasius friction correlation for laminar flow

$$c_{f \text{ Laminar}} = \frac{0.664}{\sqrt{\text{Re}_x}}$$

The simulation was performed using a preconditioned LU-SGS solver. The initial CFL of 0.7 was gradually increased to 7 after a delay of 600 cycles. HLLC fluxes were used with the van Albada limiter. The far field and initial conditions were set to 11 m/s, 101,280 Pascals, and 294.4 °K (~Mach 0.032). Molecular viscosity was computed from temperature using the Sutherland formula. The k- $\omega$  2006 turbulence model of Wilcox [2] was used without a wall function.

### 3.0 Turbulent Flow over Flat Plate with Blowing

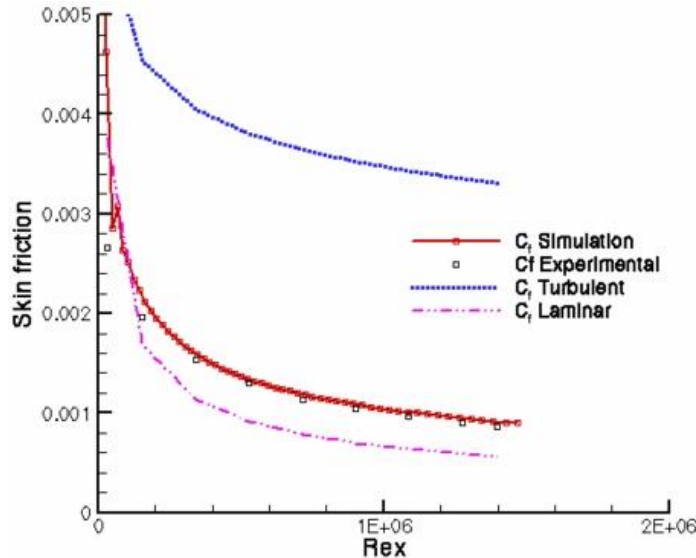


**Fig. 3: Grid and no-slip wall data for simulation of flow over plate with blowing.**

This validation test case is based on the experimental work of Anderson, Kays, and Moffat [3] who used porous plates composed of sintered bronze particles with diameters ranging from 0.0023 to 0.0007 inches. The porosity was approximately 40%. The total length of the porous plates was 96 inches. The tunnel was run at approximately ambient pressure and temperature. The far field velocity was approximately 31 ft./s. The ratio of blowing velocity to far-field velocity was set to either 0.0, 0.001, 0.002, 0.00375, or 0.008.

The kinematic viscosity was approximately  $1.59 \times 10^{-4} \text{ ft}^2/\text{s}$  without blowing. Julien, Kays, and Moffat [4] indicated that the turbulence intensity of the wind tunnel was 0.8%.

Figure 3 displays the grid and no-slip wall parameters used to simulate flow over a flat plate with blowing. In this case, the blowing velocity is set to 0.00375 times the far-field velocity. There was no transfer of heat to the walls (adiabatic).



**Fig. 4: Friction along wall for turbulent flow over flat plate with blowing.**

In Figure 4, the friction curve from the simulation is a good fit to experiment and is well under the friction correlation for fully turbulent flow over a non-porous (solid) plate but still above the friction correlation for laminar flow.

The simulation was performed using the preconditioned LU-SGS solver. The initial CFL of 0.7 was gradually increased to 7 after a delay of 600 cycles. HLLC fluxes were used with the SUPERBEE limiter. The far field and initial conditions were set to 9.4488 m/s, 97,052 Pascals, and 290.15 °K (~Mach 0.028). The  $k-\omega$  2006 turbulence model of Wilcox [2] was used without a wall function.

The  $k-\omega$  turbulence model of Wilcox [5] has also been used. The results for various values of blowing velocity are summarized in Table 1.

**Table 1: Summary of  $k-\omega$  and  $k-\omega$  2006 fit to experiment with blowing.**

$v_w/U_\infty$	$k-\omega$ 2006 error	$k-\omega$ error
0.001	3%	6%
0.002	0.7%	4%
0.00375	2.5%	5%
0.008	10%	-6%

## References

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