COMPUTATION OF WAKE / EXHAUST MIXING DOWNSTREAM OF ADVANCED TRANSPORT AIRCRAFT

Todd R. Quackenbush*, Milton E. Teske**, and Alan J. Bilanin*
Continuum Dynamics, Inc., Princeton, New Jersey 08543

Abstract

The mixing of engine exhaust with the vortical wake of high speed aircraft operating in the stratosphere can play an important role in the formation of chemical products that deplete atmospheric ozone. An accurate analysis of this type of interaction is therefore necessary as a part of the assessment of the impact of proposed High Speed Civil Transport (HSCT) designs on atmospheric chemistry. This paper describes modifications to the parabolic Navier-Stokes flow field analysis in the UNIWAKE unified aircraft wake model to accommodate the computation of wake/exhaust mixing and the simulation of reacting flow. The present implementation uses a passive chemistry model in which the reacting species are convected and diffused by the fluid dynamic solution but in which the evolution of the species does not affect the flow field. The resulting analysis, UNIWAKE/PCHEM (Passive CHEMistry) has been applied to the analysis of wake/exhaust flows downstream of representative HSCT configurations. The major elements of the flow field model are described, as are the results of sample calculations illustrating the behavior of the thermal exhaust plume and the production of species important to the modeling of condensation in the wake. Appropriate steps for further development of the UNIWAKE/PCHEM model are also outlined.

Nomenclature

A	pre-exponential term in Arrhenius rate equation
C_m	concentration of species m
c_m	fluctuating component of concentration
c_p	specific heat
E	activation energy
g_i	gravitational vector
k	thermal conductivity normalized by ρc_p
k_f	forward reaction rate
k_r	reverse reaction rate
p	pressure
q	turbulent kinetic energy
R	universal gas constant
r	radial distance inside vortex
r_b	Betz vortex subcore radius
r_c	small vortex core radius
s	wing semispan
T	temperature
T_o	reference ambient temperature
U_i	total velocity in ith Cartesian direction
u_i	fluctuating component of velocity in ith direction
V	swirl velocity in vortex wake
$\dot{W}_m$	net production rate of species m
X_m	mole fraction of mth species
x_i	ith Cartesian direction
β	temperature exponent in Arrhenius rate constant
Γ	bound circulation of the wing
η, η', η''	stoichiometric weighting variables
Λ	turbulence macroscale
ν	kinematic viscosity
ρ	density
σ	spread in Gaussian distributions
$(\bar{\ })$	mean value of quantity ( )

* Senior Associate, Senior Member - AIAA
** Senior Associate
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Introduction

The mixing of the engine exhaust with the vortical wake of high speed aircraft operating in the stratosphere can play an important role in the formation of chemical products that deplete atmospheric ozone. An accurate analysis of this type of interaction is therefore necessary as a part of the assessment of the impact of proposed High Speed Civil Transport (HSCT) designs on atmospheric chemistry. This report will describe modifications to the UNIWAKE unified aircraft wake analysis to accommodate the computation of wake/exhaust mixing and the simulation of reacting flow. The present implementation uses a passive chemistry model in which the reacting species are convected and diffused by the fluid dynamic solution produced by UNIWAKE but in which the species themselves do not affect the flow field. The resulting analysis, UNIWAKE/PCHEM (Passive Chemistry) will be described in following sections, after a discussion of the technical background for the present work.

The general topic of aircraft wake behavior has been the subject of substantial research since the 1940's, though interest has been particularly intense since the late 1960's, motivated by interest in the aircraft wake hazard problem as well as in the effect of the wakes of aircraft on the upper atmosphere. The previous work in this area laid the groundwork for present efforts to carry out a coupled analysis of plume/wake dynamics and atmospheric chemistry.

Early studies of exhaust plumes included several efforts in the late 1940's and early 1950's on forecasting the appearance of vapor trails for high-altitude aircraft (Refs. 1 and 2). This work at first neglected or greatly simplified the modeling of the aircraft wake, though Scorer and Davenport (Ref. 3) later supplemented this work with a more complete study of the interaction of contrails and aircraft wakes in the presence of a stratified atmosphere. This involved identifying mechanisms leading to the entrainment and detrainment of buoyant exhaust gases as well as the decay of the organized flow associated with the descending vortex pair. At about this same time, considerable interest arose in aircraft wake behavior in the upper atmosphere because of concern over dispersion of combustion products from supersonic commercial aircraft. Papers by Overcamp and Fay (Ref. 4), Conti, et al, (Ref. 5), Holdeman (Ref. 6), and Nielsen et al. (Ref. 7) are representative of this work, which focused on the entrainment and dissipation of the exhaust plume in the vortex wake downstream of the aircraft.