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Review

Modeling of turbulent free shear flows

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ABSTRACT

The modeling of turbulent free shear flows is crucial to the simulation of many aerospace applications, yet often receives less attention than the modeling of wall boundary layers. Thus, while turbulence model development in general has proceeded very slowly in the past twenty years, progress for free shear flows has been even more so. This paper highlights some of the fundamental issues in modeling free shear flows for propulsion applications, presents a review of past modeling efforts, and identifies areas where further research is needed. Among the topics discussed are differences between planar and axisymmetric flows, development versus self-similar regions, the effect of compressibility and the evolution of compressibility corrections, the effect of temperature on jets, and the significance of turbulent Prandtl and Schmidt numbers for reacting shear flows. Large-eddy simulation greatly reduces the amount of empiricism in the physical modeling, but is sensitive to a number of numerical issues. This paper includes an overview of the importance of numerical scheme, mesh resolution, boundary treatment, sub-grid modeling, and filtering in conducting a successful simulation.

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Nomenclature

a	speed of sound
B	energy thickness
b	10% Δu thickness
b_{ij}	turbulence anisotropy tensor, $b_{ij} = \left(-\tau_{ij}^T - \frac{2}{3}\bar{\rho}k\delta_{ij}\right)/2\bar{\rho}k$
D_{jet}	jet nozzle diameter
e	internal energy
h	enthalpy
k	turbulent kinetic energy
l	turbulent length scale
M_a	acoustic Mach number, U_{jet}/a_∞
M_c	convective Mach number, Eq. (9)
M_g	gradient Mach number, $\|S\|l/a$
M_{jet}	jet Mach number, U_{jet}/a_{jet}
M_t	turbulent Mach number, $\sqrt{2k}/a$
NPR	nozzle pressure ratio
P	pressure
Pr	Prandtl number
q_j	heat flux
R_{ij}	rotation rate tensor
r	velocity ratio, u_2/u_1
$r_{0.5}$	radial location where velocity is half of centerline value
S_{ij}	strain rate tensor
s	density ratio, ρ_2/ρ_1
Sc	Schmidt number
T	temperature
t	time
u	axial velocity
U_c	convective velocity, Eq. (8)
U_{jet}	jet mean velocity
u	velocity
x	axial coordinate
x_c	potential core length shifted to align peak centerline turbulence values
x_i	spatial coordinates
x_W	potential core length given by Witze relation
δ_{ij}	Kronecker delta
δ'	mixing layer growth rate
δ_{pit}	pitot thickness
δ_{vis}	visual thickness
δ_ω	vorticity thickness
ϵ	turbulent dissipation rate
ϵ_d	dilatation dissipation
λ_s	velocity-density parameter
μ	viscosity
ω	specific turbulent dissipation rate
Π^{dil}	pressure dilatation, $\Pi^{dil} = \frac{1}{2}\Pi_{ij}\delta_{ij}$
Π_{ij}	pressure-strain correlation tensor, $\Pi_{ij} = \overline{P'\left(u''_{i,j} + u''_{j,i}\right)}$
$\mathcal{P}$	production of turbulent kinetic energy, $\mathcal{P} = \tau_{ij}^T \tilde{u}_{i,j}$
ρ	density
σ	spread rate parameter
τ_{ij}	stress tensor
τ	turbulent time scale
θ	momentum thickness
ζ	turbulent enstrophy

Subscripts/superscripts

D	deviatoric tensor, $S_{ij}^D = S_{ij} - \frac{1}{3}S_{kk}\delta_{ij}$
inc	incompressible
jet	jet
L	laminar
T	turbulent
sgs	sub-grid scale
1, 2	mixing layer streams
∞	freestream

Operators

{}	trace of the contained tensor expression
$\bar{u}$	RANS time averaged or LES spatial filtered velocity
$\tilde{u}$	RANS density-weighted time average or LES density-weighted spatial filtered velocity
u'	RANS fluctuating velocity
u''	RANS density-weighted Favre-fluctuating velocity

1. Introduction

When asked what are the most challenging turbulent flow problems facing computational fluid dynamics (CFD) for aerospace applications, those involved in model development and application would probably identify one of many wall bounded issues. These include the difficulty in predicting adverse pressure gradient flows, flow separation, and reattachment; streamline curvature; corner flows; shock wave boundary layer interaction; turbulence transition; and heat transfer. Each of these contribute to the ability to predict aerodynamic drag, engine inlet performance metrics such as pressure recovery, and thermal loading. However, turbulent free shear flows such as mixing layers, jets, and wakes also play an important role in aeropropulsion applications. These types of flow involve the motion of fluid that is away from solid surfaces.

Modern subsonic commercial aircraft are typically configured with high-bypass ratio turbofan engines in which the bypass fan stream mixes with the high energy exhaust flow of the core engine. This mixing may occur in the aft portion of the nozzle or in the plume region. The level of noise generated by these exhaust flows increases non-linearly with jet velocity and correlates with the turbulent kinetic energy in the shear layer. Many concepts for reducing jet noise have been investigated over the past several years and resulted in significant reductions in jet noise relative to two decades ago. Lobed mixers, chevron nozzles, tabs, fluidic injection, and plasma actuators are some of the concepts that have been explored to increase mixing of the exhaust streams and modify the turbulence characteristics in the jet. Other concepts have been designed to modify the directivity of the noise away from ground observers. This is accomplished by offsetting the core and bypass streams or inserting flow deflection devices into the bypass stream in order to divert more of the lower-energy fan flow below the core stream.

With regulations on aircraft noise becoming ever more stringent, the ability to predict and potentially modify the flowfield to eliminate these sources has been an active research area. Tools based upon an acoustic analogy use the mean flow and turbulence fields from CFD solutions of the Reynolds-averaged Navier–Stokes (RANS) equations to estimate noise levels. Alternatively, large-eddy simulation (LES) can be used to directly compute the unsteady pressure fluctuations in the jet. In these simulations, prediction of both the mean flow and turbulence fields are needed in order to assess the noise of the exhaust nozzle.

Knowledge of the spreading rate of the exhaust flow is also needed in order to address potential plume interaction with the control surfaces of the aircraft and to assess the vulnerability of military aircraft to infrared plume signature detection. For air-breathing hypersonic vehicles, the size and weight of the supersonic combustion ramjet (scramjet) are driven by how rapidly the fuel and oxidizer can be mixed to enable complete combustion.

Wake flows are another important type of free shear flow. As aircraft approach for landing, the unsteady wake generated by the landing gear and control surfaces of the wing generate