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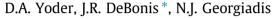
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Review

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					
а	speed of sound	δ_{pit}	pitot thickness		
В	energy thickness	δ_{vis}	visual thickness		
b	$10\% \Delta u$ thickness	δ_{ω}	vorticity thickness		
b_{ij}	turbulence anisotropy tensor, $b_{ij} = \left(- au_{ij}^T - rac{2}{3}ar ho k\delta_{ij} ight)/2ar ho k$	ϵ	turbulent dissipation rate		
D_{jet}	jet nozzle diameter	ϵ_d	dilatation dissipation		
e	internal energy	λ_{s}	velocity-density parameter		
h	enthalpy	μ	viscosity		
k	turbulent kinetic energy	ω	specific turbulent dissipation rate		
l	turbulent length scale	Π^{dil}	pressure dilatation, $\Pi^{dil}=rac{1}{2}\Pi_{ij}\delta_{ij}$		
M_a	acoustic Mach number, $U_{ m jet}/a_{\infty}$	_			
M_c	convective Mach number, Eq. (9)	Π_{ij}	pressure-strain correlation tensor, $\Pi_{ij} = P' \left(u_{i,j}'' + u_{j,i}'' ight)$		
M_g	gradient Mach number, $ S l/a$	${\cal P}$	production of turbulent kinetic energy, $\mathcal{P} = \tau_{ii}^T \tilde{u}_{i,j}$		
M_{jet}	jet Mach number, U_{jet}/a_{jet}	ho	density		
M_t	turbulent Mach number, $\sqrt{2k}/a$	σ	spread rate parameter		
NPR	nozzle pressure ratio	$ au_{ii}$	stress tensor		
P	pressure	τ	turbulent time scale		
Pr	Prandtl number	θ	momentum thickness		
q_j	heat flux	ζ	turbulent enstrophy		
R_{ij}	rotation rate tensor				
r	velocity ratio, u_2/u_1	Subscripts/superscripts			
$r_{0.5}$	radial location where velocity is half of centerline value	D	deviatoric tensor, $S_{ij}^D = S_{ij} - \frac{1}{3}S_{kk}\delta_{ij}$		
S_{ij}	strain rate tensor	inc	incompressible		
S	density ratio, $ ho_2/ ho_1$ Schmidt number	jet	jet		
Sc T		L	laminar		
t t	temperature time	T	turbulent		
	axial velocity	sgs	sub-grid scale		
u U _c	convective velocity, Eq. (8)	1, 2	mixing layer streams		
U_{jet}	jet mean velocity	∞	freestream		
u	velocity				
X	axial coordinate	Operators			
χ_{c}	potential core length shifted to align peak centerline	{}	trace of the contained tensor expression		
٠٠.	turbulence values	ū	RANS time averaged or LES spatial filtered velocity		
χ_i	spatial coordinates	ũ	RANS density-weighted time average or LES		
χ_W	potential core length given by Witze relation		density-weighted spatial filtered velocity		
δ_{ij}	Kronecker delta	u'	RANS fluctuating velocity		
δ'	mixing layer growth rate	u"	RANS density-weighted Favre-fluctuating velocity		
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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

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