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Reynolds analogy in combustor modeling

Lei-Yong Jiang *, Ian Campbell

Gas Turbine Laboratory, Institute for Aerospace Research, National Research Council Canada, 1200 Montreal Road,
M-10, Ottawa, Ontario, Canada K1A 0R6

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Abstract

The Reynolds analogy concept has been used in almost all turbulent reacting flow RANS (Reynolds-averaged Navier–Stokes) simulations, where the turbulence scalar transfers in flow fields are calculated based on the modeled turbulence momentum transfer. This concept, applied to a diffusion flame model combustor, is assessed in this paper. Some of the numerical results, obtained from a flamelet combustion model with the turbulent Prandtl/Schmidt number varying from 0.25 to 0.85, are presented and compared with a benchmark experimental database. It is found that the turbulent Prandtl/Schmidt number has significant effects on the predicted temperature and species fields in the combustor. This is also true for the temperature profile along the combustor wall. In contrast, its effect on the velocity field is insignificant in the range considered. With an optimized turbulent Prandtl/Schmidt number, both velocity and scalar fields can be reasonably and quantitatively predicted. For the present configuration and operating conditions, the optimal Prandtl/Schmidt number is 0.5, lower than the traditionally used value of ~0.85. This study suggests that for accurate prediction of turbulence scalar transfers in practical reacting flows, the Reynolds analogy concept should be improved and new approaches should be developed.

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Keywords: Reynolds analogy; Turbulence scalar transfer; Combustor modeling; Schmidt number; Prandtl number

1. Introduction

Accurate prediction of temperature distribution is critical in the development of advanced combustion systems. For example, poor temperature profiles at the liner and exit of a gas turbine combustor can significantly reduce lifetime of the combustor and turbine vanes and blades behind. In extreme cases, devastating structural damage to engine components can occur.

In almost all turbulent reacting flow RANS simulations, turbulence scalar transfers (mixture fraction, species, and energy or temperature) are calculated based on the Reynolds analogy concept. In this approach, the turbulent Prandtl (Pr_t) and Schmidt (Sc_t) numbers are used to link the turbulence scalar transfers in flow fields to the momentum transfer that is determined by a selected turbulence model.

An existence of an analogy between the wall shear and heat flux in boundary layers was first postulated by Reynolds over a century ago [1]. This original hypothesis has been considerably amended and applied to general turbulent heat and species transfers [2,3]. Recently, its applications to high-Mach-number boundary layers [4], turbine flows [5] and film cooling [6] have been studied. The Reynolds analogy factors for flow parameters related to hypersonic propulsion and turbines have been determined [4,5].

The suitability of Reynolds analogy to disturbed turbulent thermal boundary flows has been reported by a number of authors. Choi and Orchard [7] investigated the heat transfer characteristics over a triangular-profiled riblet surface, while de Souza et al. [8] studied the large-scale organization of a boundary layer disturbed by a cylinder wake flow. They all pointed out that this concept did not hold in these disturbed boundary flows. Vogel and Eaton [9] carried out heat transfer and fluid dynamic measurements downstream of a backward-facing step. It was found that Reynolds analogy failed in the recovering boundary

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[*] Corresponding author. Tel.: +613 993 9235; fax: +613 952 7677.
E-mail address: leiyong.jiang@nrc-cnrc.gc.ca (L.-Y. Jiang).

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Nomenclature

C_p	specific heat at constant pressure
D	molecular diffusivity
f	mixture fraction
f''	fluctuating component of mixture fraction
H	total enthalpy
h	heat transfer coefficient
k	turbulence kinetic energy
Le	lewis number
M	molecular weight
p	probability density function
Pr_l	laminar Prandtl number
Pr_t	turbulent Prandtl number
r	radial coordinate
S	energy source term
Sc_t	turbulent Schmidt number
St	Stanton number
T	temperature
U	mean axial velocity
U_∞	free stream velocity
u	axial velocity component
$\mathbf{V}$	velocity vector
$\mathbf{v}''$	fluctuating velocity vector
v	radial velocity component
$u''v''$	turbulence shear stress, $\overline{\rho u''v''}/\bar{\rho}$
x	coordinate along the combustor axis of symmetry
Y	species mass fraction
y^+	non-dimensional parameter, $\sqrt{\tau_w/\rho}y/\upsilon$
y	distance to the wall boundary
Z	mass fraction of element

Greek symbols

Γ_t	turbulent Prandtl or Schmidt number
ε	turbulence dissipation rate
μ	laminar viscosity
μ_t	turbulent viscosity
ρ	density
τ_w	wall shear stress
υ	kinematic viscosity
ϕ	species mass fraction, mixture fraction, or total enthalpy
ϕ''	scalar fluctuation component
φ	species mass fraction, density or temperature
ω	species source term

layer, and it was only valid far downstream of the reattachment point. Time-resolved gas temperature in the oscillating turbulent flow of a pulse combustor tail pipe was studied by John and Keller [10]. The results indicated that the analogy between momentum and thermal transport at the tail pipe wall was no longer valid.

Since the 1970s, the Reynolds analogy concept has been further extended into computational simulations of general turbulent reacting or mixing flows. The main advantage of this approach is that the turbulence scalar transfers can be effectively computed from the modeled momentum transfer without solving a full second moment closure for both momentum and scalar transportations. Consequently, the computing time to reach a converged solution is much reduced.

Numerous experimental studies on Pr_t and Sc_t were carried out in the last century, particularly in the period of 1930s–1970s [2,3]. Hinze [2] reviewed a large number of experimental measurements in pipe and 2D channel flows, and pointed out that the overall Pr_t or Sc_t varied from 0.6 to 0.8. Recently, based on their velocity and concentration half-width measurements in axisymmetric jets of air and helium, Panchapakesan and Lumley [12] obtained an average value of 0.7 for Sc_t.

In most turbulent reacting or mixing flow simulations, it has become a common practice to set $Le \equiv Sc_t/Pr_t = 1$ or $Pr_t = Sc_t$ [11]. Traditionally a constant value of $Pr_t = Sc_t \approx 0.85$ has been used in jet flows [13,14] and gas turbine combustor modeling [15,16]. However, low Pr_t and Sc_t numbers from 0.20 to 0.5 have been used by a number of authors for simulating kerosene-fired gas turbine combustors. Crocker et al. [17] successfully modeled an entire combustor from the compressor diffuser exit to the turbine inlet, including air split and liner wall temperature prediction. A low value of 0.25 was used for Pr_t and Sc_t since it consistently demonstrated better agreement with the combustor fuel/air mixing results. Kaaling et al. [18] systematically studied five RQL (rich burn, quick quench, lean burn) low-emission combustor designs. The CFD calculations were calibrated against CARS (coherent anti-Stokes Raman spectroscopy) temperature measurements, and good agreement was found by using $Pr_t = Sc_t = 0.2$. Large eddy simulations (LES) of a Rolls–Royce production gas turbine combustor were performed by Cannon et al. [19], where $Pr_t = Sc_t = 0.5$. Moreover, the effect of Schmidt number on turbulence scalar mixing of a gaseous jet issued into a cross airflow was investigated by He et al. [20]. By comparison with the available experimental data, $Pr_t = Sc_t = 0.2$ was recommended.

To provide a benchmark database for the evaluation and development of various physical models, a series of experiments were performed on a diffusion flame model combustor at the National Research Council of Canada (NRCC). The comprehensive results include mean and fluctuating velocity components, mean temperature, wall temperature, radiation heat flux, as well as species concentrations [21].

The objectives of the present work are to find out if such a low value of Pr_t and Sc_t is a real physical fact in combustor modeling, and to assess the Reynolds analogy concept

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