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A dynamic detached-eddy simulation model for turbulent heat transfer: Impinging jet

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ABSTRACT

In this study, the simulation of wall heat transfer in impinging jets is comprehensively investigated. A new turbulent thermal diffusivity formulation conjugated with a dynamic delayed detached-eddy simulation (DDES) model is proposed, based on a strict assessment and a detailed analysis of the near-wall performance of constant-coefficient DDES/IDDES and LES models. The simulations are conducted at a nozzle-to-wall distance of $H/D = 2$ and 4 with a Reynolds number of $Re = 40{,}000$. The measurement data obtained by temperature-sensitive paint (TSP) and particle image velocimetry (PIV) are used for validation. Impinging jets at $Re = 23{,}000$ and 70,000, in accordance with the literature, are used for further validation. The definition of the shielding function in a previous version is modified by using an alternative formulation, which is averaged only in a thin layer near the wall and is not sensitive to the computational domain size. A α_t model is proposed for impingement heat transfer, using a constant Pr_t model in the impingement region and a shear rate-based α_t formulation in the wall-jet region. The dynamic DDES model conjugated with the new α_t model accurately predicts the wall Nusselt number distributions in each impinging jet. The LES and dynamic DDES conjugated with the existing Pr_t model underestimate the heat transfer coefficient in the wall-jet region, due to the insufficient eddy resolving capacity that cannot compensate for the turbulent eddy viscosity attenuation in the heat transfer model. The constant-coefficient DDES and improved DDES (IDDES) produce excessive turbulent eddy viscosity in the flow, leading to the high model-dependence of the results.

1. Introduction

Accurately predicting turbulent flow and wall heat transfer, which is closely related to near-wall turbulence and energetic flow structures, is essential when assessing the performance of thermal processes such as jet impingement heat transfer. Among all numerical approaches, the cost-effective Reynolds-averaged Navier-Stokes (RANS) methods yield the mean flow and thermal quantities highly dependent on turbulence models; alternatively, the large-eddy simulation (LES) method which determines spatio-temporally varying quantities has received widespread attention [1,2]. In LES simulations, the prediction of the wall heat transfer relies on the sufficient resolving of small-scale structures superimposed in the turbulent boundary layer, which dramatically raises the grid resolution requirement and thus the computation cost. Detached-eddy simulation (DES) models [3] can alleviate this specific problem through a hybrid approach, in which a portion of the boundary layer is modeled using RANS, whereas most of the domain is resolved using LES. Accordingly, predicting turbulent heat transfer with the DES-based approach is highly desirable.

Given the cause-and-effect relationship between turbulent flow and wall heat transfer, construction of a novel DES approach for accurate prediction of the near-wall turbulence and the energetic flow structures is essential. DES was originally designed to model the attached boundary layer using RANS whereas LES is applied in the separated flow regions [4]. Despite the success in most wall-bounded turbulent flows with a steady inflow condition, the original DES model suffered from the problematic behavior of grid-induced separation (GIS) [5]. This resulted from modeled stress depletion (MSD) [6] when the grid was refined to shift from RANS to LES without balancing the reduction of eddy viscosity from the resolved turbulence content. A delayed DES (or DDES) was thus proposed to prevent this switch in the boundary layer region by using a generic formulation of the shielding function, which depends on the eddy-viscosity, the local velocity gradient, and the wall distance [6,7]. However, simulation of the channel

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Nomenclature

B	dimensionless scalar defined for the buffer layer
C_k	dynamic DDES model coefficient
C_e	dynamic DDES model coefficient
C_α	constant coefficient in α_t model
D	Nozzle diameter
d_w	wall distance of the computational nodes
F_1	first blending function in SST formulation
F_2	second blending function in SST formulation
f_d	shielding function in DES models
f_t	blending function in α_t model
h_{max}	maximum grid length scale
h_{min}	minimum grid length scale
H	Wall-to-nozzle distance in impinging jet
k	turbulent kinetic energy at the grid level
K	turbulent kinetic energy at the test level
l	length scale defined in the dynamic DDES model
L	length scale defined in turbulent eddy viscosity formulations
p	pressure enclosure model
P_k	production term in dynamic DDES model
Q_{ij}	intermediate quantity to compute Pr_{sgs}
q_w	joule heating on the FTO glass
q_c	heat loss induced by the lateral conduction.
q_r	heat loss induced by the radiation
r	radial coordinate
S	strain-rate tensor
t	time
T	temperature
T_0	reference (room) temperature
$\boldsymbol{U}$	velocity vector at the grid level
U_0	mean (bulk) axial velocity at the nozzle exit
U_{mag}	mean velocity magnitude
U_r	mean radial velocity
$u_{r,rms}$	Root-mean-square of the radial velocity
V	grid element volume
x	coordinate
y	coordinate
y^+_{local}	non-dimensional grid length scale defined in dynamic DDES model
z	coordinate
Nu	Nusselt number
$\overline{Nu}$	mean Nusselt number
Re	Reynolds number ($=\frac{U_0 D}{\upsilon}$)
Pr	Prandtl number
Pr_{sgs}	subgrid-scale Prandtl number

Greek symbols

α	thermal diffusivity
α_t	turbulent thermal diffusivity
ρ	density
υ	kinematic viscosity
υ_t	turbulent eddy viscosity
φ_d	damping function in dynamic DDES model
ω	turbulent eddy frequency
Ω	vorticity
Δ	filter width at the grid level
$\widehat{\Delta}$	filter width at the test level, $\widehat{\Delta} = 2\Delta$

Abbreviations

DES	detached-eddy simulation
DDES	delayed detached-eddy simulation
IDDES	improved delayed detached-eddy simulation
LES	large-eddy simulation
PIV	particle image velocimetry
RANS	Reynolds-averaged Navier-Stokes
TSP	temperature-sensitive paint

flow using both DES and DDES models identified a log-layer mismatch (LLM) problem [8,9]; two logarithmic layers with different intercepts were produced, which resulted in the under-prediction of the skin friction [10]. The improved DDES (IDDES) was developed with a series of blending functions and a modified filter width [7,10]. This model improved on LLM and ensures automatic selection of DDES or wall-modeled LES modes (WMLES, in which RANS is applied only to a thin layer of the near-wall region where the wall distance is much smaller than the boundary layer thickness [11]) depending on the turbulence content of the flow. He et al. [12] recently proposed a new dynamic DDES model, in which the model coefficients were dynamically computed, along with the dynamic adjustment of the RANS area, to achieve the WMLES mode. This model exhibited a more rapid RANS-to-LES transition in the free and separated shear layers than the constant-coefficient DES models and showed better performance in highly inhomogeneous turbulent flows.

Compared with turbulent flow simulations, very few efforts have been sought to deal with model formulations for wall heat transfer prediction. In heat transfer simulations, a thermal diffusion formulation α_t is usually assumed as the ratio of the turbulent eddy viscosity υ_t to a constant turbulent Prandtl number Pr_t [13]; or alternatively, dynamic Pr_t models are used together with υ_t in α_t formulation [14]. Therefore, α_t varies within a small range in the whole computational domain, giving rise to poor prediction for certain types of heat transfer, such as impinging jets at small nozzle-to-wall distances. Impinging jets are important and effective heat transfer configurations and are commonly used as a wall heat removal mechanism in gas turbine cooling and aircraft de-icing [15]. The mean Nusselt number distribution on the impingement wall features a second peak in the radial direction when the nozzle-to-wall distance is smaller than the length of the jet potential core [16,17]. This presents a challenge in accurate reproduction of the wall Nusselt number distributions, even for LES and hybrid simulations. Current heat transfer models have been found to capture the second peak of the mean Nusselt number distribution at small nozzle-to-wall distances when the grid resolution is sufficiently high. However, the discrepancy between the predicted Nusselt number value and the measurement data remains large, even with tens of millions of computational grids. Hadžiabdić and Hanjalić [13] conducted LES simulations for an impinging jet at $Re = 20{,}000$ and with a nozzle-to-wall distance of $H/D = 2$. The results showed that the second peak of the mean Nusselt number was missing using a full domain with 9.9 million grid elements, whereas the discrepancy was as large as 20% beyond the second-peak location, when a quarter domain with 7.5 million grid elements was used. A similar heat transfer discrepancy between the simulation results and measurement (or DNS) data were observed in [18] using 7.23 million grid elements, and even in [19] using 26 million grid elements with a six-order discrete scheme. This strongly suggested that the insufficient grid resolution for the heat transfer prediction as for the heat transfer characteristics were closely associated with the small-scale structures near the wall. The prediction can be improved by further increasing the grid resolution, but it exponentially increases the computation cost. The alternative strategy is to model the highly Reynolds