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Numerical investigation of twin-jet impingement with hybrid-type turbulence modeling

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HIGHLIGHTS

- LES & SST–SAS hybrid model were applied for the first time for impinging twin-jets.
- The numerical investigation was carried out for different spacing and Reynolds number.
- Both approaches were not able to produce accurate results for heat transfer.
- SST–SAS produced good results in terms of pressure distribution & velocity.

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ABSTRACT

A Computational Fluid Dynamics (CFD) study of a twin-jet impingement is performed using the Reynolds-Averaged Navier–Stokes (RANS) approach with a dynamic Smagorinsky Large Eddy Simulation (LES). The use of a hybrid RANS–LES (i.e., part of the turbulence is modeled and part of the turbulence is resolved) method potentially offers a compromise between the computational efficiency and the accuracy comparable with that of a pure dynamic LES. In the current study, the SST–SAS (Shear-Stress transport with Scale-Adapted Simulation) k–ω model having hybrid RANS–LES characteristics is utilized for turbulence modeling. Effects of nozzle-to-plate (H/D) and nozzle-to-nozzle (L/D) distances on the pressure distribution and the heat transfer are investigated for $3 \times 10^4 < \mathrm{Re} < 5 \times 10^4$. Numerical results of SST–SAS and dynamic LES methods are validated against available experimental data. The flow expands radially as H/D increases. Results show that the SST–SAS model can produce fairly accurate results, especially with a lower H/D at which the sub-atmospheric region appears. In addition, the SST–SAS model is capable of predicting the peak values of local Nusselt number at correct locations.

1. Introduction

Impinging jets are the important elements to various industrial processes, such as paper and aircraft industries, cooling of electronic circuits and gas turbine. A vertical/short take-off and landing (VSTOL) aircraft operating close to the ground is highly dependent on the twin-jet impingement behaviors. Literature reviews show that many studies are available concerning the single-jet impingements which mainly deal with the heat transfer characteristics. However, twin jets are less investigated in terms of the flow structure and interactions, and there are a few experimental data available for the velocity and pressure distributions.

Single impinging jets are applied to concentrated heating and cooling while in many applications, multiple jets are required to cool or heat a large area. Thus, a detailed understanding of the complex flow structure associated with impinging jets can be beneficial in optimizing and improving their performance. Amano and Brandt [1] investigated the features of the turbulent structure of impinging jets with experimental means. Lytle and Webb [2] studied the characteristics of impinging jets for different nozzle-to-plate spacings with a range of Reynolds numbers. The twin-jet vorticity structures are experimentally investigated by Cornaro et al. [3]. In their work, they compared different arrangements of twin jets with different spacings between two jets, and concluded that the geometrical properties have a dominant effect on the flow structure. The velocity distribution of multiple jets has been studied in the works of Barata [4]. He noticed that a fountain shape flow field is the common feature of twin jets, independent of the spacing between jet slots. Ozmen [5] and Abdel-Fattah [6] performed some

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Nomenclature

C_p	pressure coefficient
C_μ	eddy-viscosity coefficient
$\overline{C}_s$	Smagorinsky coefficient
D	diameter of jet
$F_{1,2}$	model blending function
G	filter function
H	nozzle-to-plate distance
k	total turbulent kinetic energy
L	jet-to-jet distance/turbulent length scale
L_{vK}	von Karman length scale
L_{ij}	Leonard stress
Nu	Nusselt number
Pr	Prandtl number
Pr_t	turbulent Prandtl number
P_ω	rate of production of ω
P_k	rate of production of k
Re	Reynolds number
$\overline{S}_{ij}$	mean strain-rate tensor
T	temperature
$\overline{u}_i$	averaged velocity in i-direction
y^+	dimensionless wall distance ($u_\tau y/\nu$)
β	turbulent model constant
$\delta_{i,j}$	Kronecker's delta
$\overline{\Delta}$	grid-filter width
ζ	turbulent model constant
κ	von Karman constant
ν,ν_T	laminar and turbulent eddy viscosities
ρ	density
ω	specific turbulent dissipation rate
$\sigma_{\varepsilon,\omega}$	turbulent Schmidt number
$\tau_{i,j}$	turbulent stress tensor
LES	large Eddy Simulation
RANS	Reynolds averaged Navier–Stokes
SST	Shear stress transport
SAS	scale-adaptive simulation

Subscript

i,j	variable numbers
w	wall

tests on twin jets with different spacings for nozzle-to-plate and jet-to-jet; a subatmospheric region has been found between two jets. He also concluded that with increasing the nozzle-to-plate distance this region gets smaller.

Yang and Shyu [7] investigated the heat transfer characteristics of impinging jets with an inclined surface. Their work showed that with increasing the inclination angel the maximum Nusselt number occurs downstream of the impingement area. Salmanzadeh et al. [8] applied v^2-f model to study flow characteristics of axisymmetric turbulent impinging jets. They focused on the thermal distribution around the impinging zone. The particle image velocimetry (PIV) was applied in the work of Radhouane et al. [9]. They studied the effect of a cross flow on twin tandem jets in terms of temperature distributions. They also carried out a numerical simulation using the Reynolds Stress Model (RSM). It was concluded that the cross flow has a dominant effect on the thermal characteristics of the jets.

Most of the works available in the literature are about the computations of twin jets with different k-ε turbulence models. One of the earliest attempts is the work carried out by Chuang and Nieh [10]. They applied a standard k-ε model for twin jets with a confinement wall and a cross flow. The results were compared with the experimental data conducted by Sarippalli [11]. The velocity and pressure distributions showed a good agreement with the available data. Gabray and Kaminski [12] applied k-ε model to study turbulent impinging jets on a cylindrical surface. Comparing their results with the works of Hwang and Cho [13], they found that at high Reynolds numbers, the k-ε model performs quite well.

The effects of Reynolds number and different spacings between the slot jet and the impingement plate are also examined by Seyedein et al. [14]. In their study, the Reynolds number varied between 5×10^3 and 2×10^4 and the analysis was carried out for $2.5 < H/D < 7.5$. Fernandez et al. [15] investigated the flow structure for square twin jets using the standard k-ε and realizable k-ε models. They concluded that both the models are incapable of predicting the flow features at the impingement region. The heat transfer characteristics of the round jet array in different cross flow orientations are examined by Miao et al. [16]. Their results showed that with increasing Reynolds number, the Nusselt number also increases.

Recently, there is a growing interest in applying the Large Eddy Simulation (LES) to predict the flow field and heat transfer characteristics of impinging jets. Li et al. [17] applied an LES for simulating the jet impingement structure underneath an aircraft. The WALE (Wall-Adapting Local Eddy-viscosity) sub-grid scale model is utilized in their work. They compared the results with experiments and found a good agreement in terms of mean velocity distributions and normal stresses.

According to the above-mentioned studies on impinging jets, twin-jets are much less investigated in terms of the CFD framework. There is almost no reported research on the application and performance evaluation of an SST–SAS method in the modeling of twin jets. In the present work, a hybrid-type RANS–LES approach based on the SST–SAS k-ω method is applied to investigate the ability of the model to predict the complex flow and heat transfer characteristics of twin jets for different nozzle-to-plate ($1 < H/D < 4$) and nozzle-to-nozzle ($0.5 < L/D < 2$) spacings. The study is carried out for a range of Reynolds numbers $3 \times 10^4 < \mathrm{Re} < 5 \times 10^4$, providing a suitable condition to validate the capability of the SST–SAS approach. For better comparisons, the results are also compared against pure LES computations based on the dynamic Smagorinsky SGS (Sub-grid Scale) model. The current hybrid RANS–LES model falls in the unified DES (Detached Eddy Simulation) approach devised by Strelets [18], in which the turbulence in the boundary layers is modeled (RANS) and the large detached eddies are resolved (LES). In DES, the switch between the RANS and LES is dictated by the ratio of the RANS to the LES turbulent length scales.

2. Governing equations

2.1. SST–SAS model

The SAS is an alternative method to DES in which the RANS model is not influenced by the grid spacing. It is based on the SST k-ω turbulence model and modifies SST by adding a source term with the ω-equation to account for unsteadiness. In collaboration with RANS equations, the SST–SAS model solves transport equations for the turbulent kinetic energy k and the specific dissipation rate ω [19,20]: