Numerical studies of heat transfer characteristics by using jet discharge at downstream of a backward-facing step

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Summary. This study presents the numerical predictions of the fluid flow and heat transfer characteristics for a backward-facing step by discharging a jet perpendicularly to the main flow. The turbulent governing equations are solved by a control-volume-based finite-difference method with power-law scheme and the well known $K - \varepsilon$ model and its associate wall function to describe the turbulent behavior. The interesting parameters include entrance Reynolds number ($Re_h$), dimensionless jet location ($X_j/H$) and the ratio of jet velocity ($U_j/U_o$) with channel expansion ratio $ER = 1.67$. The predicted attachment point is in good agreement with the experiment. It is found that the optimum position is at $X_j/H = 2.1$ ($X_j$: location of jet measured from the step position, $H$: the step height).

Notation

- $B$: nozzle width
- $C_1, C_2, C_u$: turbulent constant
- $D$: channel height
- $ER$: expansion ratio, $D + H/D$
- $G$: generation rate of turbulent kinetic energy
- $H$: step height
- $h_a$: local heat transfer coefficient
- $J$: velocity ratio, $U_j/U_o$
- $K$: turbulent kinetic energy
- $q''$: heat flux
- $Re_a$: Reynolds number based on step height, $U_0H/\nu$
- $S_e$: source term
- $T$: temperature
- $U_o$: inlet velocity
- $U_j$: jet velocity
- $U_f$: friction velocity
- $U_x, V$: $x, y$ component velocity
- $X_j$: position of discharging jet
- $X_R$: reattachment length of the main flow
- $X_{JR}$: reattachment length of the upper discharging jet flow
- $y^+$: dimensionless distance from the wall
- $\phi$: dependent variables
- $\Gamma_h$: turbulent diffusion coefficient
- $\mu_e, \mu_o, \mu_T$: effective, laminar, turbulent viscosity
- $\rho$: density
1 Introduction

The flow downstream of a backward-facing step has been studied by many investigators. Abbott and Kline [1] used a visualisation technique involving dye, as well as a hot-film anemometer, in measuring the velocity profiles of water flowing over single and double steps. The flow pattern and reattachment length were found to be unchanged with \(Re_h\) (based on the step-height, \(H\)) ranging from 10,000 to 125,000, and for a variation in the inlet turbulence intensity from approximately 1 to 18% of the mainstream velocity. Seban [2] measured in particular the distributions of temperature and velocity normal to the wall for the separated region downstream of the step and upstream of the reattachment region. The maximum augmentation of heat transfer occurred about 6 step-heights downstream of the step. He found that the usual postulates in a “law of the wall” approach, the assumptions of a uniform shear stress and local equilibrium, were inaccurate in the separated region. Aung and Goldstein [3] used a Mach-Zehnder interferometer to measure the temperature distributions of air flowing downstream of the step. Relatively low Reynolds number flows (\(Re_h\) ranging from 700 to 1900) were studied and with the upstream as well as the downstream walls heated to constant temperature. They found that \(\text{Nu}_{\text{max}}\) occurred at 4.5 step-heights downstream of the step. Their results also indicated that the mixing layer and near-wall sublayer were both important parameters on the heat transfer in the separated region. Eaton and Johnston [4] have provided a review of the literature in this area. They summarized that five factors influence the reattachment length. Aung [5] made detailed temperature measurements of laminar flows downstream of a step, using the Mach-Zehnder interferometer. He presented that streamline curvature caused the streamlines upstream of the step to become essentially parallel to the wall (instead of moving away from it as in the normal growth of an attached boundary layer). The conclusion is that the numerical calculation of flows over steps may need to begin upstream of the step at least in the case of low \(Re_h\) flows to include this effect. Armaly et al. [6] presented heat transfer, mass transfer and fluid dynamic data for relatively low Reynolds number. The peak of the Sherwood number was clearly upstream of reattachment for turbulent flows, but both the Sherwood and Nusselt number showed a double peak for laminar flows.

Armaly et al. [7] experimentally investigated the hydrodynamic behavior, such as the reattachment length and the velocity profiles of a laminar duct flow with a backward-facing step. The experiments reported by Simpson et al. [8] suggested that the near-wall region of separated flow is substantially different from the corresponding region in an ordinary boundary layer. Combined heat transfer and fluid dynamic measurements in a separated and reattaching boundary layer, with emphasis on the near-wall region are presented by Vogel et al. [9]. It was found that the fluctuating skin friction controlled the heat transfer rate near reattachment, while the conventional Reynolds analogy applied in the redeveloping boundary beginning two or three step heights downstream of reattachment. Sparrow et al. [10] investigated the reattachment length and the location of the maximum heat transfer rate for laminar flow in a channel with a step by using the vorticity-stream function approach. The existence of the recirculation region provides high heat transfer performance near the reattachment point as presented by Sparrow and Chuck [11].