CHEMICAL ENGINEERING RESEARCH AND DESIGN 92 (2014) 229–239

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Prediction of local pressure drop for turbulent flow in axisymmetric sudden expansions with chamfered edge

*Youngmin Bae**, *Young In Kim*

Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon 305-353, Republic of Korea

ABSTRACT

The present study numerically investigates the turbulent flow in axisymmetric sudden expansions with a chamfered edge. With the aid of commercial CFD software, Fluent 12.0, an extensive set of numerical simulations is carried out for dimensionless chamfer lengths varying from 0.02 to 0.5, expansion ratios between 2 and 6, and chamfer angles of up to 45° at a Reynolds number of 3×10^5. First, we present and analyze the local pressure drop across the sudden expansions without a chamfer. The dependence of the pressure drop coefficient on the main geometric parameters is then thoroughly investigated. Finally, a new correlation is proposed for the local loss coefficient in sudden expansions with a chamfered edge, along with a discussion of the optimal chamfer angle.

Keywords: Pressure drop; Sudden expansion; Chamfer; Turbulent flow

1. Introduction

Flow resistance continues to be one of the key issues in the design of fluid systems such as oil pipelines, steam lines, water conduits, and air ducts. Since it is closely associated with the pumping power requirements for the operation of a piping system and eventually for the entire plant, the pressure drop in a pipe, diffuser, orifice, venturi, or converging nozzle has been of prime importance to the design of the fluid loops. In particular, the pressure drop in a sudden expansion has received a lot of attention over the past decades, as it is frequently encountered in a variety of engineering applications.

There have been voluminous investigations of a flow in a sudden expansion. Oliveira and Pinho (1997) investigated numerically the local loss coefficient in axisymmetric sudden expansions under a fully developed velocity profile at the inlet, and compared the numerical results with the quasi-one-dimensional theory for the pressure drop in the expansion flows. In their later contribution (Oliveira et al., 1998), a general correlation of the irreversible loss coefficient was proposed for the laminar flow of a Newtonian fluid in axisymmetric sudden expansions having a diameter ratio of 1.5–4 and Reynolds number between 0.5 and 200, while other works have considered the pressure losses in the laminar non-Newtonian flow (Halmos et al., 1975; Pinho et al., 2003). The details of laminar axisymmetric sudden expansion flows such as the distance to the reattachment, redevelopment length, and strength of the recirculating flow have also been widely investigated through a flow visualization technique (Back and Roschke, 1972; Monnet et al., 1982) and particle image velocimetry (PIV) measurements (Hammad et al., 1999). For the case of a turbulent flow, the axial development of the mean velocities and turbulence quantities has been studied experimentally for several configurations of sudden expansion (Stevenson et al., 1984; Durrett et al., 1988; Gould et al., 1990; Devenport and Sutton, 1993). The behavior of a suddenly expanding axisymmetric flow in the turbulent regime has also been analyzed numerically with a discussion of the reattachment length (Teyssandier and Wilson, 1974), self-sustained precession of the flow field (Guo et al., 2001), and growth of azimuthal structures (Tinney et al., 2006).

Several research efforts have been devoted to studying the flow characteristics and pressure recovery performance of a sudden expansion with some modifications, e.g., an introduction of a fence in the diffusion zone (Mandal et al., 2011), and the addition of a center body downstream of the nozzle exit (Devenport and Sutton, 1993). On the other hand, few studies have been done in the area of axisymmetric sudden

* *Corresponding author*. Tel.: +82 42 868 4528; fax: +82 42 868 8990.
E-mail addresses: ybae@kaeri.re.kr, ominbae@gmail.com (Y. Bae).
Received 22 April 2013; Received in revised form 21 June 2013; Accepted 16 July 2013
0263-8762/$ – see front matter
http://dx.doi.org/10.1016/j.cherd.2013.07.016

Nomenclature

C_1, C_2, C_μ, S	constants in the model transport equations
D_0	inlet pipe diameter
D_2	outlet pipe diameter
k	turbulence kinetic energy
L_0	inlet pipe length
L_2	outlet pipe length
L_d	chamfer length
n_{ar}	expansion ratio
P	pressure
ΔP_f	frictional loss
ΔP_t	total pressure drop
r	radial coordinate
Re	Reynolds number
S_{ij}	mean strain tensor
U_i	time-averaged velocity component in the i direction
u_i	fluctuating velocity component in the i direction
U_0	mean velocity at the inlet
U_x	axial velocity component
x	axial coordinate
x_i	Cartesian coordinate in the i direction
$\Delta x_{min}, \Delta r_{min}$	minimum grid spacing
y^+	non-dimensional wall distance
α	chamfer angle
α_{opt}	optimal chamfer angle
α_{lim}	upper limit of chamfer angle
δ_{ij}	Kronecker delta
ε	rate of turbulence kinetic energy dissipation
ζ	pressure drop coefficient
ζ_0	pressure drop coefficient in the sudden expansion without chamfer
$\eta, \sigma_\varepsilon, \sigma_k$	constants in the model transport equations
λ_0, λ_2	friction coefficients
μ	dynamic viscosity of fluid
ν	kinematic viscosity of fluid
ν_t	turbulent viscosity
ρ	density of fluid
ω	specific dissipation rate

expansions with a chamfered edge, although this is a more relevant configuration in practice. For example, Idelchik and Fried (1986) dealt with a diffuser of a circular cross-section with stepped walls, which can be viewed as an axisymmetric sudden expansion with a chamfered edge. However, this work was only dedicated to a diffuser slenderness (L_d/D_0) of larger than 0.5, and focused on the optimal angle that gives the minimum pressure loss. Thus, there still exists a need to further investigate the details of a turbulent flow through sudden expansions with a chamfered edge. In addition, the effects of the chamfer angle, expansion ratio, and chamfer length on the pressure drop coefficient have not been addressed yet, particularly for the cases of $L_d/D_0 < 0.5$, although they are of great importance in many applications.

In the present study, a suddenly expanding axisymmetric flow has been numerically investigated for a Reynolds number of $Re = 3 \times 10^5$. The main objective of this paper is to study the local loss coefficient of a turbulent flow in an axisymmetric sudden expansion having a slight chamfer on the edge. With this aim, an extensive set of numerical simulations in a total of 410 cases are carried out using a commercial computational fluid dynamics (CFD) code, Fluent 12.0. We scrutinize the impacts of the chamfer angle, expansion ratio, and chamfer length on the pressure drop in sudden enlargements, along with a discussion of the relevant flow features. A new correlation of the irreversible loss coefficient is also proposed for axisymmetric sudden expansions with a chamfered edge. The remainder of this paper is organized as follows. Section 2 is devoted to the computational setup and sensitivity test. The local loss coefficient in a sudden expansion with a chamfered edge is then discussed in Section 3. Finally, conclusions are stated in Section 4.

2. Computational setup

Simulations are performed for the steady, incompressible, axisymmetric, and turbulent flow of a single-phase constant-property Newtonian fluid. The description of the turbulence models, numerical methods, and CFD model employed are presented in this section, including the influence of the mesh resolution and turbulence model.

2.1. *Solution methodology*

In the present study, Reynolds Averaged Navier–Stokes (RANS) equations are used to model the turbulent flow in a sudden expansion with a chamfered edge. The RANS equations read as

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial U_i U_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \overline{u_i u_j}\right] \tag{2}$$

where the overbar indicates the time-averaging, ρ is the density of the fluid, ν is the kinematic viscosity, u_i and U_i are the fluctuating and mean velocities, respectively, and P is the pressure. In the two-equation eddy viscosity models used in this study, the Reynolds stress tensor in Eq. (2) is given by

$$\overline{u_i u_j} = \frac{2}{3}\delta_{ij}k - \nu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{3}$$

where δ_{ij} denotes the Kronecker delta, k is the turbulent kinetic energy, and ν_t is the turbulent viscosity. In the realizable k–ε turbulence model (Shih et al., 1995), which is primarily used throughout this study, the transport equation for the turbulent kinetic energy k can be written as

$$\frac{\partial U_i k}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] - \overline{u_i u_j}\frac{\partial U_i}{\partial x_j} - \varepsilon \tag{4}$$

for the turbulent dissipation rate ε,

$$\frac{\partial U_i \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_1 S\varepsilon - C_2\frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} \tag{5}$$

where

$$C_1 = \max\left[0.43, \frac{\eta}{\eta + 5}\right], \quad \eta = S\frac{k}{\varepsilon}, \quad S = \sqrt{2S_{ij}S_{ij}},$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{6}$$