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Flow uniformizing distribution panel design based on a non-uniform porosity distribution

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ABSTRACT

The conditions required for a flow resistance element to uniformize a non-uniform flow in a two-dimensional channel were derived in terms of a non-uniform porosity profile. The validity of this approach was confirmed through a numerical analysis over a wide range of parameter conditions. The proposed equation for the non-uniform porosity distribution gave satisfactory results for a wide variety of velocity profiles at the channel inlet. For sufficiently thick orifices, the equation was valid over a wide range of average porosities, from 0.3 to 0.6. For thin orifices, satisfactory uniformity was obtained only for a mean effective porosity over a narrow range of 0.42–0.48. Two different methods of generating variable porosity, using a constant hole size plus variable blocking plates or using a constant blocking plate size plus variable holes, did not show any appreciable difference in results.

1. Introduction

A uniform flow environment is essential in a variety of engineering systems. A wind tunnel is a typical example where a uniform flow enables the generation of predictable fields of flow velocity, temperature, and concentration around obstacles installed within a channel (Hancock, 1998; Moonen et al., 2007). Also, the overall performance of heat and mass transfer is optimized under uniform flow conditions in a variety of engineering applications, including heat exchangers (Bassiouny and Martin, 1984; Wen and Li, 2004), electronics cooling (Choi et al., 1993a, b; Kim et al., 1995; Wang et al., 2001), various air conditioning systems (Cheng et al., 1998; Luo and Tondeur, 2005; VanGilder and Schmidt, 2005), solar heat collectors (Weitbrecht et al., 2002), and electrostatic precipitators (Sahin and Ward-Smith, 1987), to name a few. Typical process equipment related to uniform flow distributions includes various chemical reactors such as contactors, mixers, burners, extrusion dies, and textile-spinning chimneys (Commenge et al., 2002; Kareeri et al., 2006; Perry et al., 1984). In recent years, uniform flow distributions have been a concern in fuel cells and biological systems (Aricò et al., 2000; Bi et al., 2010; Danilov and Tade, 2009; Huang et al., 2008; Kee et al., 2002; Lee et al., 2009; Li and Sabir, 2005; Wang et al., 2010).

Small-scale non-uniformities decay naturally with time due to the action of viscosity, but macroscopic velocity profiles tend toward fully developed profiles in the presence of walls and are inherently non-uniform. Therefore, a uniform velocity profile can be maintained only artificially, such as by installing flow-resistance devices within the flow passage. The non-uniform pressure drop due to the non-uniform resistance and flow velocity redistributes the flow. Perforated plates or diffusers used in electrostatic precipitators (Şahin and Ward-Smith, 1991) and multiple screens used in wind tunnels are typical examples of flow-resistance devices (Hancock, 1998; Moonen et al., 2007). Another example is a successively bifurcating tube network used in fuel cells to supply uniform flow to each terminal exit (Liu et al., 2010, 2012).

In its simplest design, a uniformizing baffle has a uniform flow resistance or uniform flow opening (Hancock, 1998). Even when the flow opening or flow resistance is uniform across a non-uniform flow, a uniformizing effect emerges because the pressure drop across a resistance element in a turbulent flow is proportional to the square of the flow velocity. But although the use of a uniform resistance device can reduce the level of non-uniformity, the original velocity

Abbreviations: C_d, discharge coefficient [dimensionless]; D, hole diameter [m]; $f(y)$, normalized velocity profile ($=V/V_0$); H, channel height [m]; L, channel length [m]; $\dot{m}$, mass flow rate [kg/s]; N, number of holes [EA]; ΔP, pressure drop through the distribution panel [Pa]; P_0, pressure at the inlet [Pa]; P_2, pressure after the distribution panel [Pa]; S, distance between the inlet and the distribution panel [m]; t, panel thickness [m]; $V(y)$, velocity profile across the flow cross-section [m/s]; V_0, average velocity [m/s]; W, length of the separating plate [m]; β, local porosity ($=D/(D+W(y))$) [dimensionless]; β^*, effective porosity ($=\beta C_d$) [dimensionless]; β_0, average porosity [dimensionless]; ρ, density [kg/m^3]

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profile remains to some degree, and a uniform velocity profile is never attained. Thus, in practical approaches, a non-uniform resistance distribution has been sought through numerical simulation or experimental means (Allan and Hamdan, 2006; Fan et al., 2008; Liu et al., 2010; Mohammadi et al., 2013).

Most of the effort till date to obtain a non-uniform resistance distribution to improve flow uniformity has been case specific, and general theory or models are lacking. It is thus the aim of this study to propose a simple theoretical model for flow uniformization in the most general sense and to validate it through numerical simulation. Porosity is used as an intermediate parameter representing the flow resistance, and a non-uniform distribution of porosity is sought to uniformize a non-uniform flow supplied at the inlet of a two-dimensional (2-D) channel. The flow field was analyzed numerically to check the validity of the proposed model over a wide range of operational and model parameters.

2. Analysis of flow flattening with a non-uniform flow resistance

When a turbulent flow passes through a resistance element, the flow velocity profile changes depending on the distribution of the flow resistance across the flow cross section. Considering the continuity constraint, the flow velocity is reduced after passing through a high-resistance zone and is increased after a low-resistance zone. When the flow resistance is produced by a perforated plate, the local flow field around each hole can be simply modeled by flow through an orifice.

When a single orifice is installed in a tube with a turbulent flow of velocity V_0, the pressure drop (ΔP) across the orifice changes with the orifice opening or porosity (β_0) (Perry et al., 1984).

$$\Delta P = \tfrac{1}{2}\rho V_0^2\left[\frac{1}{\beta_0^2}-1\right]\frac{1}{C_d^2} \tag{1}$$

Here, C_d is the discharge coefficient, which is close to 0.6 for sharp-edged orifices and 1.0 for long orifices with rounded entrances over a wide range of Reynolds numbers. If a sharp orifice is used, a normal velocity component emerges over the orifice plane, and some discrepancy can be expected between experiments and one-dimensional (1-D) predictions. Long slits were used in the numerical analysis for this study to facilitate stable computation and better agreement with 1-D modeling. C_d=1.0 was used for most of the cases shown in the results; a sharp slit was analyzed for one case and compared against the 1-D prediction together with discussions on the choice of C_d value.

If a turbulent flow entering a tube with a non-uniform velocity profile, $V(y)/V_0=f(y)$, has a uniform velocity and pressure after passing through a perforated zone of non-uniform porosity $\beta(y)$ (Fig. 1), the porosity distribution $\beta(y)$ required to obtain flow uniformity can be obtained from Eq. (4), starting from the modified 1-D Bernoulli equations expressed as Eq. (2), where β_0 is a reference porosity or a sort of average porosity. Although the equations were formulated for a velocity profile that is non-uniform in only one direction normal to the flow, the same equation may hold even for a flow with non-uniformity in two dimensions if the pressure loss occuring due to transverse spreading just upstream of the perforated zone is negligible compared to the pressure loss through the perforated zone.

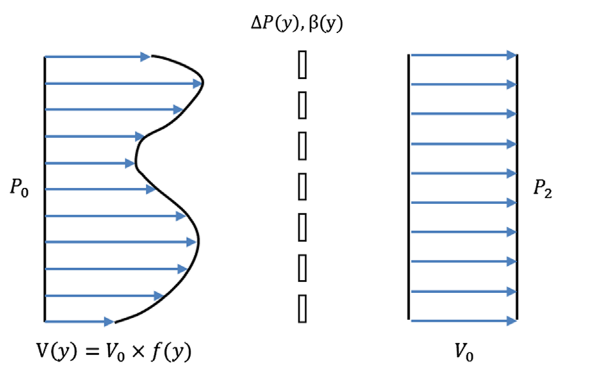

Fig. 1. Schematic diagram of the system and conditions used for the analysis.

$$P_0+\tfrac{1}{2}\rho[V(y)]^2-\Delta P = P_2+\tfrac{1}{2}\rho V_0^2 \tag{2}$$

$$\tfrac{1}{2}\rho V_0^2[1/\beta(y)^2-1]=\tfrac{1}{2}\rho V_0^2[1/\beta_0^2-1]+\tfrac{1}{2}\rho V_0^2[f(y)^2-1]C_d^2 \tag{3}$$

$$1/\beta(y)^2 = 1/\beta_0^2+[f(y)^2-1]C_d^2 \tag{4}$$

$$1/[\beta^*(y)]^2 = 1/[\beta_0^*]^2+[f(y)^2-1] \tag{5}$$

In Eq. (5), $\beta(y)$ is the apparent porosity defined from the geometric opening, and $\beta^*(y)=\beta(y)C_d$ is the effective porosity based on the vena contracta for each hole. The average porosity β_0 is arbitrary, but there exists a theoretical optimum for β_0 that minimizes the 2-D effects, and also a practical optimum considering a large pressure loss with a small β_0 and a long developing distance after passing through an orifice with a large β_0.

Since the modified Bernoulli's equation, Eq. (1), holds good for any coordinate system, if only applied along streamlines, the equations above can be extended to problems with velocity variation in two dimensions, $V(y, z)$, as in Eq. (6).

$$1/[\beta^*(y,z)]^2 = 1/[\beta_0^*]^2+[f(y,z)^2-1] \tag{6}$$

3. Computational method and procedure

3.1. Model geometry for analysis

The modeled system consisted of a straight 2-D channel of constant height H. The perforated zone (distribution panel) was made of a linear array of N units of hole–plate pairs of thickness t (Fig. 2). Each unit had a hole of gap D and two platelets of length $W/2$ on two sides of the hole. The local porosity was easily varied as $\beta=D/(D+W)$ by varying either D or W. When a finite number of holes is used, it is not always possible to design the geometry to provide the exact desired porosity. In such a case, W (or D) can be modified slightly with N and D (or W) fixed, resulting in a porosity profile slightly different from the desired value but within 1–2%. The panel designed using Eq. (4) for $V(y)/V_0=2y/H$ is shown in Fig. 3 as an example, where the number of holes was N=40 and the hole-to-hole distance (or W) varied with the hole size (D) uniform. Also shown is the 3-D plate made of holes instead of slits to the same porosity distribution.

3.2. Numerical technique

To obtain a numerical solution for the flow field, the continuity equation and the 2-D Reynolds-averaged Navier–Stokes equations

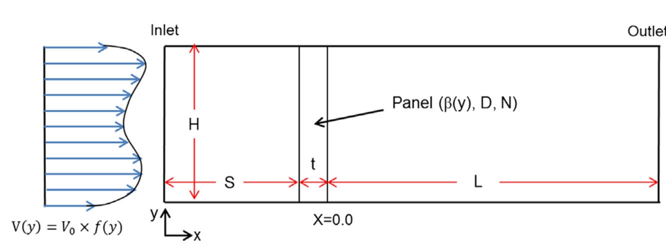

Fig. 2. Schematic diagram of the computational domain. An example of the panel geometry is shown in Fig. 3.