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Effects of geometric structures on flow uniformity and pressure drop in dividing manifold systems with parallel pipe arrays

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ABSTRACT

Dividing manifold systems have been extensively used in the areas of energy transfer and conservation. The design of uniform flow distribution is a critical issue for the enhancement of performance of the manifold system. In this study, the effects of the inlet Reynolds number and structural parameters (area ratio (AR), pipe pitch (Δl), height of convex head (h_{head}) and number of outlets (n)) on flow uniformity and pressure drop in the DMS–PPA have been numerically investigated and validated with experiment data. The non-uniform distribution in the manifold system has been quantified using the dimensionless parameter β_i (flow ratio) and Φ (non-uniformity coefficient). The results indicate that the flow rate increases along the longitudinal direction of the manifold and becomes close to the average value in the 2nd and 3rd outlets. It is found that the Φ slightly drops with the Re rising, while the ΔP_j would dramatically increase owing to the increasing inlet flow rates. The AR has the greatest influence on flow uniformity, and lower AR corresponds to a more uniform distribution. The corresponding Φ values increases from 0.00351 to 0.3885 when AR varies from 0.2844 to 4. Under the same inlet flow rate, the increase of n will lead to obvious flow non-uniformity. The superiority of flow performance in the DMS–PPA can be ascribed to the anti-parallel flow direction, and the 'plenum chamber-like' structure of the manifold. The optimsed geometric structures with $1 < AR < 1.5$, and $\Delta l = (\phi_{o_i} + \phi_{o_{(i+1)}} + 120)$ mm are recommended, considering the synergetic effect of flow uniformity and pressure drop. This study can provide a reference for engineers in designing dividing manifold systems.

1. Introduction

The manifold system is extensively applied in many energy transfer processes, including chemical, biomedical, mechanical, agricultural, as well as in building and environmental engineering. A manifold is defined as a flow channel in which fluid enters or leaves through porous side walls or lateral pipes owing to the action of differential pressure [1]. Generally, manifolds commonly used in flow distribution systems can be classified into four types: dividing manifolds, combining manifolds, parallel (Z-type), or reverse (U-type) flow manifold systems, as illustrated in Fig. 1 [1]. In many industrial devices, it is observed that severe flow mal-distribution problems exist in manifolds with an increasing number of lateral branches. Some pipes may be associated with inadequate fluids, while others may have them in excess, which is attributed to different pressure drops [2]. A uniform flow distribution plays an essential role in industrial processes because it is beneficial to provide better heat transfer, temperature control, and a lower pressure drop, which is translated into higher efficiency and durability of industrial facilities and devices [3–5]. A designer has to be familiar with the exit pressure drop and the extent of non-uniformity in flows through lateral branches for a given heat input and flow rate.

To date, great efforts have been made to investigate the characteristics of flow distribution in manifold systems, including theoretical analyses, experimental measurements, and computational fluid dynamics. A pioneering work was conducted by Acrivos et al. [2], whereby the Bernoulli equation was modified by adding a correction momentum term. They derived a normalised governing equation by using a modification of the friction factor on Blasius law. Considering that it is difficult to analyse the separated effects of friction and momentum, Bajura [1] developed the first general theoretical model for flow distribution based on mass and momentum conservation. The pressure recovery factor was directly defined.

Since then, a series of attempts were made to develop a generalised theoretical framework and unified the existing theoretical models. Wang [6] firstly solved a generalised governing equation of flow distribution and pressure drop in Z-type configurations of

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Nomenclature

AR	area ratio, $\left(AR = \sum_{i=1}^{n} \frac{\pi\phi_{oi}^2}{4} / \frac{\pi\phi_{in}^2}{4}\right)$
DMS–PPA	dividing manifold system with parallel pipe arrays
Eu	Euler number, $\left(Eu_{d/c} = \frac{\Delta P}{\frac{1}{2}\rho v_{in/out}^2} = \frac{p - p_{in/out}}{\frac{1}{2}\rho v_{in/out}^2}\right)$
h_{head}	height of convex head (mm)
L	length of dividing manifold (mm)
L_{pipe}	length of inlet/outlet pipe (mm)
l_1	distance between the inlet and the bottom of left head (mm)
l_2	distance between the inlet and the first outlet (mm)
l_3	distance between the last outlet and the bottom of right head (mm)
Δl	pipe pitch, $(\Delta l = \phi_{oi} + \phi_{o(i+1)} + s)$ (mm)
n	number of outlets
Δp_j	total pressure drop between two sections (Pa)
Q_i	mass flow rate of each outlet (kg/s)
$\overline{Q}$	average mass flow rate (kg/s)
Q_{in}	mass flow rate of inlet (kg/s)
$R_{in/o}$	curvature radius at inlet/outlet T-junction (mm)
S	source term in Eqs. (1)–(3)
s	operating distance between lateral pipes (mm)
v_{in}	velocity in inlet cross-section (m/s)
$v_{manifold}$	velocity in cross-section of dividing manifold (m/s)
x	distance from the vertex of left convex head in the longitudinal direction of dividing manifold (mm)

Greek symbol

β_i	flow ratio for each outlet defined in Eq. (4)
$\overline{\beta}$	average flow ratio
ρ	density (kg/m^3)
φ	generalised independent variable in governing equations
Γ_φ	diffusion coefficient of φ in turbulent flow
Φ	non-uniformity coefficient of flow distribution defined in Eq. (5)
ϕ_{in}	diameter of inlet pipe (mm)
ϕ_{oi}	diameter of the ith outlet pipe (mm)
$\phi_{manifold}$	diameter of cross-section of dividing manifold (mm)

fuel cells, based on mass and momentum conservation. His models were then extended into various layout configurations of manifolds using a new discrete approach [7]. Midoux and Tondeur [8] proposed a theoretical overview of the flow distribution through manifolds consisted of parallel channels. The mesoscopic governing equations of the momentum and energy balances were developed, and the correction coefficients were reviewed, compared, and synthesised. However, it is unknown whether the unified theory is applicable to an arbitrary configuration of manifold and varying correction coefficients based on simplified assumptions. Additionally, the complicated equation solving process depends on the computer program, which is inconvenient for the design and optimisation of manifolds. It has been a well-known challenge in the field of manifold systems to identify its general solution.

Recently, with the rapid increase in computer capacity and the development of user-friendly CFD (Computational Fluid Dynamics) programme interfaces, the CFD technique has been extensively employed to predict the flow distribution in manifold systems. Researchers mainly focused on the effect of geometrical parameters on the flow distribution [9–17] and optimised the configurations of manifold systems [10,18–25]. The geometrical parameters included the dimensions of the manifold/lateral pipes, flow area ratios, flow directions, etc. The research results showed that a larger manifold area with longer channel lengths corresponds to a more uniform flow distribution [9]. The simplest way to achieve uniform distribution is based on the direct enlargement of the header diameter [10]. It is also found that reducing the branching tube size or increasing the entrance settling distance will improve the flow distribution [11]. The interactive influences of key structural parameters in a heat exchanger have been studied by Zhou et al. [12]. Additionally, in terms of the configuration optimisation, the tapered manifold [18–19], modified inlet/outlet location [20], and the introduction of orifices and nozzles in the manifold [21] constitute extensively used strategies. Besides, Huang et al. [22] used the Levenberg–Marquardt method to construct the shapes of manifolds and successfully improved the distribution in a Z-type heat exchanger.

Despite the significant progress that has been achieved in manifold systems over the past few decades, a unified methodology for improving flow uniformity at T-junctions has been lacking, especially with multiple T-junctions in the manifold system owing to complex flow distributions and inlet flow conditions. The dividing

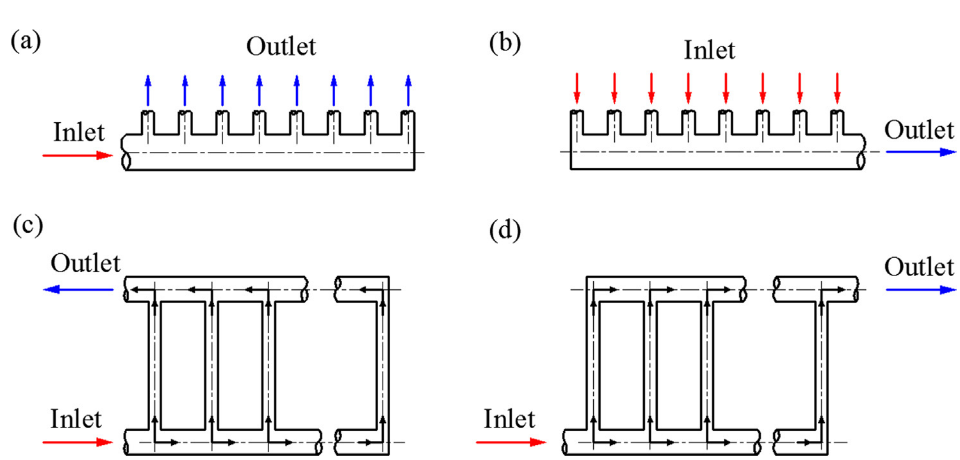

Fig. 1. Four types of manifolds: (a) dividing flow; (b) combining flow; (c) reverse flow (U-type); (d) parallel flow (Z-type) [1].