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Theory of flow distribution in manifolds

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ABSTRACT

Flows in manifolds are of great importance in quite diverse fields of science and technology, including fuel cells, spargers, solar collectors, microchannels, porous infiltration and irrigation. Theory of flow distribution and pressure drop is vital to predict process performance and efficiency of manifold systems. In this paper, we examined research and development of theoretical models and methodology of solutions in flow in manifolds and highlight remarkable advances in the past fifty years. The main existing models and solution methods were unified further to one theoretical framework, including Bernoulli theory and momentum theory, and discrete and continuum methodologies. The generalised model was applicable to not only designs of continuum manifolds but also those of discrete manifolds with constant or varying factors. The procedure of design calculation is in reality straightforward without requirements of iteration, successive approximation and computer programme. The theoretical model provides easy-to-use design guidance to investigate the interactions among structures, operating conditions and manufacturing tolerance under a wide variety of combination of flow conditions and geometries through three general characteristic parameters (E, M and ζ) and to minimize the impact on manifold operability.

1. Introduction

The flow in manifold systems is extensively encountered in many industrial processes including chemical [1–3], biomedical [4,5], mechanical [6–8] and civil and environmental engineering [9–11]. The uniformity of the flow distribution in a manifold system often determines efficiency, durability and cost of the units of the chemical and biological processes. There are two common structures of manifolds used for flow distributions: consecutive [1–11] and bifurcation [12,13].

A fractal bifurcation structure assumes that the fluid behaves tree-like where the channels at the last level have the smallest length and diameter, in the bifurcation structure (Fig. 1a) the reaction channels (last level channels) are usually the longest. The bifurcation structure is generally a good design in the absence of channel dimensional variations. It is the only one where flow distribution does not change for different flow rates at high Re. However, the equipartition is greatly depending on manufacturing tolerance and port blockage. Furthermore, when a large number of ports, a large pressure drop is expected due to turning loss and it is also more complex to design and fabricate. Therefore, it is unsuitable for those cases where additional pressure losses become important.

A consecutive manifold consists of multiple ports/holes with constant cross-sectional area as shown in Fig. 1b. In a consecutive manifold the main fluid stream entrances a manifold and branches continuously along the manifold. This type of manifolds is the most commonly used flow distributors due to their clear advantages of simplicity and less pressure drop over bifurcation structures. This means the greatest potential to reduce development and manufacturing cost and accelerate design and manufacturing cycle. However, using a consecutive manifold, a key question which arises in the design of such units is a possibility of the severe flow maldistribution problems. Some ports may be starved of fluids, while others may have them in excess, which reduces system performance and efficiency. It is a key to predict the performance and efficiency of various manifold configurations so that high efficiency and cost reduction can be achieved through an optimal geometrical structure. This paper will focus on theory of flow in consecutive manifolds due to a wide range of applications. There are three approaches to study pressure drop and flow distribution in a manifold: computational fluid dynamics (CFD) [14–19], discrete models [7,20] and analytical models [2,21,22].

The CFD is a somewhat detailed approach in which modelling has potential to resolve real-world 3-D engineering structures. The pressure drop and flow distribution can be predicted using this approach without the knowledge of flow coefficients, such as the friction and pressure recovery coefficients. However, the CFD is unsuitable for optimizing manifold geometry and preliminary designs since it is expensive to generate the computational geometry and mesh for each new configuration. Furthermore, there are still the difficulties for the turbulence models and the boundary models associated with solving swirling or curvature flows because

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Nomenclature

A	constant in Eq. (A5) (= $3Q$)
B	constant in Eq. (21), defined by Eq. (A7)
C	constant in Eq. (5)
C_1, C_2	undetermined constant in Eq. (22)
C_f	coefficients of turning losses
d, d_{ch}	diameter and hydraulic diameter of the ports (m)
D, D_h	diameter and hydraulic diameter of manifold (m)
f	friction factor
E	Ratio of manifold length to diameter (L/D)
F, F_c	cross-sectional area of manifold and port (m^2)
J	constant in Eq. (21), defined by Eq. (A11)
k	pressure recovery factor (=$(2-\beta)/2$)
l_c	length of port
L	length of manifold (m)
M	ratio of sum of all the port areas to area of manifold ($F_c n/F$)
n	numbers of ports
n_c	threshold number of ports
p	dimensionless pressure defined by Eq. (13)
p_c	dimensionless ambient pressure
$\bar{p}$	dimensionless pressure defined by Eq. (6)
P	pressure in manifold
P_c	ambient pressure
Q	coefficient in Eq. (19), defined by Eq. (17)
r, r_1, r_2	roots of characteristic equation
R	coefficient in Eq. (19), defined by Eq. (18)
u_c	dimensionless port velocity defined by Eq. (13)
U_c	port velocity (m/s)
$\bar{U}$	dimensionless velocity defined by Eq. (6) in manifold
v_c	dimensionless volume flow rate in ports
w	dimensionless velocity defined by Eq. (13) in manifold
W	velocity in manifold (m/s)
x	dimensionless axial coordinate defined by Eq. (13) in manifold
X	(m)
y	axial coordinate defined by Eq. (6) in manifold

Greek symbols

α	constant in Eq. (33)
β	average velocity ratio in manifold (W_c/W)
γ	constant in Eq. (33)
ρ	fluid density (kg/m^3)
τ	wall shear stress (N/m^2)
ζ	average total head loss coefficient for port flow
ξ	coefficient of non-smooth ducts

Subscripts

i	the *ith* section in manifold
0	the inlet of a manifold

the eddy-viscosity models failed to capture the anisotropy of strain and Reynolds stresses under the action of Coriolis and centrifugal forces [23–26].

Discrete model is also called network model. In a discrete model, a manifold is represented as a network of multiple-junctions traversed by the fluid flow. Then, mass and momentum conservation equations can be built at each junction. Finally, a set of difference equations is solved using an iteration program. Because of its relatively simplicity this approach has been used by many researchers [19,20]. However, a designer cannot use its results directly since this approach usually needs computer programme. It is still inconvenient for the preliminary design and optimisation of the manifold structures since there are no explicit relation between flow performance and manifold geometries.

Analytical model is also called the continuous model in which flow is considered to be continuously branched along a manifold. It has been shown intuitively, as well as mathematically, that the continuous manifolds are limiting cases of the discrete manifolds [2,28,29]. In mathematical viewpoint, the fluid mechanical principles in a continuous manifold lead to a differential rather than a difference equation in a discrete one. Furthermore, an explicit analytical solution can directly be converted to one solution of discrete systems. For these reasons, the continuous models are also fundamentals of various discrete models.

A main advantage of analytical models over the CFD and the discrete models is that it is simple and flexible for manifold designers since solutions based on the differential equation can be represented more simply and compactly than is the case for calculations using the non-linear difference equations. Furthermore, a generalised analytical model has unique possibility to correlate explicitly the performance, such as flow distribution and pressure drop, and manifold structures, such as diameters and shape, pitch and duct lengths. Particularly, for preliminary design, we have less information if a geometrical structure is optimal but major decisions should be made in this stage, such as cost, durability, maintenance and performance. The rational yet tractable generalised model offers possibility to explore flow performance under various geometries of manifolds.

Due to these clear advantages, analytical solutions have received fairly good attentions in the past fifty years. There are diverse models for flow distributions in manifolds which scatter in different fields. Most of the theoretical models are traditionally based on Bernoulli theorem or slight modification thereof. However, a problem raised from the experiments by McNown [30] and Acrivos et al. [31]. Their experimental results showed that there was a pressure rise after flow branching as shown in Fig. 2. This phenomenon was explained by Wang et al. [2,27–29]. Because the lower energy fluid in the boundary layer branches through the channels the higher energy fluid in the pipe centre remains in the pipe. So the average specific energies in a cross-section will be higher in the downstream than in the upstream. Since energy balance is based on the average value in the cross-section, these higher specific energies cannot be corrected and lead to an error. Hence, according to the First Law of Thermodynamics, when the specific mechanical energies are multiplied by the relevant mass flow rate terms, the mechanical energy after branching for the manifold can apparently be greater than the approaching energy. Thus, it is not surprising that a pressure rise was predicted by Bernoulli theorem, which has been observed by the experiment. Recent researchers preferred to apply momentum conservation along a manifold to avoid this problem [2,6,22,27–29]. The advantage of applying the momentum conservation is that one does not need to know detailed flow patterns and the flow process can be simplified. Any error due to simplification can be corrected with pressure recovery factor, friction factor and discharge factor.

Since both Bernoulli and momentum theory are used to describe flow in manifolds they should be identical in all the fields. In practice, there are a wide range of models in the different fields. There is much ambiguity what difference between them. Wang [27,28] did the first attempt to unify main theoretical models into one theoretical framework. He demonstrated that Bernoulli equation was just a special case of the momentum model. In this regard, a fruitfully unified perspective is now emerging—one quite natural to chemical engineers. However, there are still key issues in this field. For example, is the theory developed by Wang applicable to arbitrary shape and varying factors? Furthermore, many models on modified Bernoulli equation seem to have similar formula as those on