Applied Thermal Engineering 89 (2015) 927–945

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Discrete method for design of flow distribution in manifolds

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HIGHLIGHTS

- Discrete methodology of flow field designs in manifolds with U-type arrangements.
- Quantitative comparison between U-type and Z-type arrangements.
- Discrete solution of flow distribution with varying flow coefficients.
- Practical measures and guideline to design of manifold systems.

ARTICLE INFO

Article history:
Received 9 February 2015
Accepted 28 June 2015
Available online 6 July 2015

Keywords:
Mathematical modelling
Design
Fluid mechanics
Plate heat exchanger
Solar collector
Fuel cells
Microreactor

ABSTRACT

Flow in manifold systems is encountered in designs of various industrial processes, such as fuel cells, microreactors, microchannels, plate heat exchanger, and radial flow reactors. The uniformity of flow distribution in manifold is a key indicator for performance of the process equipment. In this paper, a discrete method for a U-type arrangement was developed to evaluate the uniformity of the flow distribution and the pressure drop and then was used for direct comparisons between the U-type and the Z-type. The uniformity of the U-type is generally better than that of the Z-type in most of cases for small ζ and large M. The U-type and the Z-type approach each other as ζ increases or M decreases. However, the Z-type is more sensitive to structures than the U-type and approaches uniform flow distribution faster than the U-type as M decreases or ζ increases. This provides a simple yet powerful tool for the designers to evaluate and select a flow arrangement and offers practical measures for industrial applications.

1. Introduction

Flow in manifold systems is one of the most common issues in science and engineering where a stream fluid needs to be subdivided into parallel sub-streams, and then combined into a discharge stream, such as fuel cells [1–5], microreactors [6–9], compact heat exchanger [10,11], radial flow reactors [12], solar collectors [13], boiler headers [14–16], electronic cooling [17,18], hydrocyclone [19–21] and nuclear engineering [22–25]. A uniform flow distribution is of paramount importance for system operation which ensures high performance and reliability. The flow field must not only provide a uniform distribution of the fluids over all the channels, but it also must provide means to maintain a low pressure drop. However channel and header dimensions can vary much in different applications. The hydraulic diameters of channels for microreactors range from several tens of micrometres to several millimetres, while the diameters for boiler or ventilation do from several centimetres to several tens of centimetres. The ratio of sum of all the channel areas to header area, M, varies from decimals to several tens. Different applications lead different theoretical models in a diverse of fields. For plate heat exchangers or boiler headers, a smaller value of M is often employed. The inertial effects may be dominated for the turbulence flows [10–12] and the frictional effects are neglected. However, for fuel cells or microreactors, flow may fall in laminar flow region. A larger value of M may be employed to maximize active reacting region of headers by reducing dead header sizes. Thus, theoretical models neglected often inertial effects [6–15]. Oversimplified structural models and incomplete understanding of the fundamental physics will, at best, lead to inconsistent results – at worst, a lot of stranded resource and wasted budget. A sound theoretical framework is the starting point from which the industry – via subsequent experiment and field demonstration – can reach the ultimate endgame of mainstream commercial acceptance.

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http://dx.doi.org/10.1016/j.applthermaleng.2015.06.069
1359-4311/

Wang [26] reviewed main theoretical models and approaches and highlighted remarkable advances in the past fifty years. However, there is still a low level of understanding of the relevant fluid dynamics in manifold systems despite a wide range of applications in science and engineering. Particularly, fuel cells and micro-reactors may amplify small design and tolerance errors due to reaction and interaction among multi-level manifolds [27–35], and therefore, require more accurate theoretical models for prediction of flow performance (flow distribution and pressure drop) occurring in a manifold system.

Discrete methods are one of most common approaches to study the flow distribution in manifolds, also named as channel network model. In a conventional channel network model, a multi-scale parallel channel networks is usually described as the lattice network using analogy with the conventional electric circuit methods [6,7,28–33]. Similar to Ohm's law, the pressure drop is assumed to be proportional to the flow rates. The relationship of pressure drop, flow rate and flow resistance is built using Darcy–Weisbach equation or Hagen-Poiseuille equation for cylindrical shape. Essentially, the linear assumption between the pressure drop and the flow rates is somewhat similar as that of Bernoulli equation in which frictional resistance is calculated using Darcy–Weisbach equation. Then, a set of linear difference equations is established using Kirchhoff's law at each junction for the distributor and collector and is solved using an iteration program. Thus, a manifold structure is represented as a network of multiple-junctions traversed by the fluid flow. An advantage of the conventional discrete methods is applicable to construct complex network due to simplified linear assumption of pressure drop and flow rate, such as new conceptual pin-type configurations [7].

However, there is a main difference between the electric current and the fluidic circuits. Unlike electric current, the flow in a manifold has inertial effects. The inertial influence may be dominant due to flow branching singularities. Furthermore, an averaged profile of the velocity is assumed in cross-section of a manifold. Thus, the lower energy fluid in the boundary layer branches through the channels and the higher energy fluid in the centre remains in the manifold. 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 using the linear assumption and may cause an error.

Attempts were performed by Pan et al. [33] to correct the singular losses due to flow turning in the manifold and sudden expansion/contraction due to flow branching. However, the values of the singular losses in a manifold system are varying with *Re* numbers. It is very difficult to evaluate singular losses in the conventional network models since flow velocities are unknown and require to be solved iteratively. Furthermore, the influence of an averaged profile of the velocity in the cross-section of a manifold could not be corrected in the conventional network method. Acrivos et al. [36] demonstrated a pressure rise resulting from the branching singularity for the dividing flow manifold more than fifty years ago. Wang et al. [22] indicated theoretically three flow regions: momentum-dominant, momentum-friction reciprocity and friction-dominant regions. The inertial effects are dominant in the momentum-dominant region. Thus, the pressure rise in a dividing flow was not captured by the conventional network approach due to neglecting of the inertial effect. The linear assumption is valid only for flow at low *Re* numbers or manifolds with a large pitch where the inertial effect can be neglected.

In order to overcome the problems of flow branching singularity and averaged velocity profile, Acrivos et al. [36] modified Bernoulli equation using a corrected term of the singular losses. Then, their model was used for both discrete and continuum manifolds. Along this way, many models were developed to address the inertial influence on flow distribution [10,15]. It was well-known challenge to develop a generalised theory and solution in the past fifty years. Wang [4,5,22,26–28,37,38] did a series of attempts to develop a generalised theoretical framework and unified main existing theoretical models into one theoretical framework for parallel channel configurations, including Bernoulli theory and momentum theory [26–28]. Firstly he made a major step forward to solve analytically a generalised governing equation of flow distribution and pressure drop of the dividing, combining, U-type and Z-type. Then he developed and solved a generalised governing equation of the Z-type [5]. In the recent years, his models were extended into various layout configurations of fuel cells with the Z-type arrangement, including single serpentine, multiple serpentine, and interdigitated [37,38] using a new discrete approach. The new approach is between the conventional network and analytical solutions. It is different from the conventional network methods and included effects of the flow branching singularity. A direct and quantitative relationship is established among flow distribution, pressure drop, configurations, structures and flow conditions. A direct, systematic and quantitative comparison of flow distributions and pressure drops among these most common layout configurations was carried out for the first time for the Z-type [37]. This represents an important step from theory to a practical design tool. The success of the new discrete method for the Z-type arrangement stimulates our thinking to develop a discrete method for a U-type arrangement.

U-type and Z-type are two typical types of manifold systems in industrial applications, as shown schematically in Fig. 1. A direct and quantitative comparison of performances is difficult between two types due to complex interactions among flow distribution, pressure drop, configurations, structures and flow conditions. It is still open issue which type has better performance. Some studies [39–42] showed that the U-type had a better flow distribution while others [43–45] had opposite results. These studies covered only limited cases for thousands of thousands of combinations of layouts, structures and dimensions, and flow conditions. These limited cases are not sufficient to prove that the U-type is better than that of the Z-type. However, this is very important to assess if the U-type under what conditions is better than that of the Z-type since we need to select which type arrangement in practical applications. Therefore, a systematic analysis is necessary to understand theoretically underlying mechanism and practically select arrangements. The primary aim of this paper is to develop a discrete method for the U-type arrangements. The second aim is to apply the method for comparison of performance between the U-type and the Z-type arrangements.

2. Theoretical model

The development of the present theoretical model is based on the following assumptions:

1) Fluid is single-phase and isothermal;
2) Headers are of constant cross-sectional area throughout the length;
3) All of channels are same size with constant cross-sectional area and equally spaced channels of uniform size between distributor and collector headers;
4) Mass and momentum conservations are based on the control volume of the T-junctions (Fig. 1).

A generalized governing equation of flow distributions in manifold systems can be derived to Eq. (1) by Wang