Review on Single-Phase Fluid Flow Distribution in Manifold

Jafar M. Hassan[1], Wahid S. Mohammed[2], Thamer A. Mohamed[3], Wissam H. Alawee[4]

[1,2] University of Technology, Department of Mechanical Engineering, Baghdad, Iraq

[3]Universiti putra Malaysia, Faculty of Engineering, Department of Civil Engineering, 43400 UPM Serdang, Selangor, Malaysia

[4]University of Technology, Department of Mechanical Engineering, Baghdad, Iraq

Abstract: ***single-phase flow distribution from a manifold into parallel channels are found in various industrial applications employing fuel cells ,agricultural irrigation systems, variety of piping system, chemical reactors, solar thermal collectors, Polymer processing, etc. the flow distribution in manifold with multi-parallel channels has been studied over the past decade. Uneven flow distribution causes a reduction in both the thermal and fluid-dynamic performance and in many cases the failure of the device. A uniform flow distribution requirement is a very common issue in many engineering applications. This task is made complicated by the flow distribution in these devices depended on the great number of variables which act together. Research on convective flow distribution in manifold of different application has been extensively conducted in the past decade. This review summarizes numerous researches on two topics; the first section focuses on studying the fluid flow behavior of different appellations. The second section concentrates on the effect design parameters on flow distribution in manifold. The purpose of this article is to get a clear view and detailed summary of the influence of several parameters such as flowrate in the header (or manifold), size of the header, diameter of the parallel channels, location and size of inlet port to the header, flow direction, shape of the channels and the headers. In addition, operating conditions and flow properties.***

Keywords: Manifold, Flow distribution, Uniformity.

1. Introduction

Flow in manifold is of great importance in many industrial processes when it is necessary to distribute a large fluid stream into several parallel streams and then to collect them into one discharge stream. The applications in which manifolds play a major role extend from traditional situations such as municipal water distribution systems and automobile engines to very recent, high-technology devices such as microchannel heat sinks and critical biological systems such as blood circulation in the human body [1].

Manifolds can usually be categorized into one of the following types [2]-[5]: dividing, combining, parallel, and reverse flow manifolds as shown in Fig. 1. Parallel and reverse flow manifolds are those which combine dividing and combining flow manifolds and are most commonly used in plate heat exchangers. In a parallel flow manifold, the flow directions in dividing and combining flow headers are the same which is generally referred as a Z-manifold. In a reverse flow manifold, the flow directions are opposite is referred as a U-manifold. A uniform flow distribution requirement is a very common issue in many engineering circumsta-nces because it has significant influence on the performance of fluidic devices such as plate-type heat exchangers, a variety of piping system, heat sinks for cooling of electronic devices, fuel cells, chemical reactors, solar thermal collectors, flow distribution systems in treatment plant, the piping system of pumping stations. Therefore, for most applications, the goal of manifold design is to achieve the uniform flow distribution through all of the outlets.

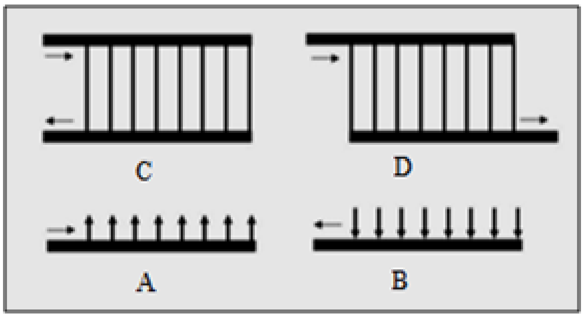

Figure 1: Different types of flow manifolds (A) dividing, (B) combining, (C) *Z*-manifold and (D) *U*-manifold

2. Flow Distribution in Manifold

A great number experimental, analytical and numerical studies deal with flow distribution in manifold. Bajura [6] developed the first general theoretical model for investigation of the performance of single-phase flow distribution for both intake and exhaust manifolds. Primary emphasis is placed on configurations in which the lateral tubes form sharp-edged junctions at right angles to the manifold axis. A mathematical model was formulated in terms of a momentum balance along the manifold. Bajura and Jones [7] extended the previous model and prediction for the flow rates and the pressures in the headers for the dividing, combining, reverse and parallel manifold configurations. They found that the uniform flow distribution in the laterals is attained only when the headers act as infinite reservoirs, and they identified the most important parameters affecting flow distribution: manifold area ratio (total lateral tube area/inlet tube area), lateral flow resistance, header length/diameter ratio, diameter ratio between headers, and friction factor of the tube. Majumdar [8] developed a mathematical model with one-dimensional elliptic solution procedure for predicting flows in dividing and combining flow manifolds. The mathematical model has been further used by Datta and Majumdar [9] for numerically investigation of flow distribution in parallel and reverse flow manifolds. In both the studies, the authors have found two non-dimensional parameters (area ratio and friction parameter) which affect the flow distribution. Pigford et al. [10] studied analytically and experimentally the flow distribution in parallel and reverse flow manifolds using air. They found that, for the same geometrical and operating conditions, reverse flow manifold provides more uniform flow distribution as compared to that in a parallel flow manifold. Bassiouny and Martin [11],[12] presented an analytical solution for the prediction of flow and pressure distribution in both the intake and exhaust conduits of heat exchanger for both types flow (U-type and Z-type) . From the analysis, a general flow distribution and the pressure drop can be determined by a general characteristic parameter m^2. Nearly uniform flow distribution may be obtained when m^2 is equal to zero. In the case when m^2 is positive, the channel flow rates will increase in the direction of the intake stream. If m^2 is negative the channel flow rates will also increase in the intake stream direction. The analysis also shows that the total pressure drop in plate heat exchangers is practically the same for both U- and Z- type arrangements. Mueller and Chiou [13] presented in a review article the factors influencing maldistribution in heat exchangers. The flow distribution from manifold has become of interest in predicting the heat transfer performance of compact heat exchangers. Often, flow rates through the channels are not uniform and in extreme cases, there is almost no flow through some of them, which result in a poor heat exchange performance.

Shen, P.I. [14] developed an analytical solution to evaluate the effect of friction on flow distribution in both dividing and combining flow manifolds. A constant cross-sectional area of the manifold header and a constant friction factor along the manifold were assumed in order to obtain the analytical solution, expressed in terms of the lateral flow distribution as a function of two performance parameters, (a) the friction parameter and (b) momentum loss parameter. Numerical results show that friction always increases flow imbalance in the combining flow configuration, but it may either increase or decrease flow imbalance in the dividing flow configuration, depending on the ratio of the lateral area to the cross-sectional area of the manifold. Choi et al. [15] studied numerically the effect of the area ratio on the flow distribution in manifolds of a liquid cooling module for electronic packaging. Results showed that the flow rate in the last channel was 2.75 times that in the first channel. It is concluded that the area ratio is one of the most important parameters affecting the coolant distribution and should be carefully examined in the design of a liquid cooling module.

Choi et al. [16] studied numerically the effect of the Reynolds number and the width ratio on the flow distribution in manifolds of a liquid cooling module for electronic packaging. They showed that the flow distribution in the manifold strongly depended on the Reynolds number, and the width ratio. The flow distribution was also improved with increasing width ratio. As the Reynolds number increased, the flow rate in the last channel significantly increased; consequently, the flows in the first several channels decreased. The flow distribution was also improved with increasing width ratio. Kim et al. [17] numerically investigated the effects of header shapes and the Reynolds number on the flow distribution in a parallel flow manifold of a liquid cooling module for electronic packaging, for three different header geometries (i.e., rectangular, triangular, and trapezoidal) with the Z-type flow direction. Their results indicated that the triangular shape provided the best distribution regardless the inlet velocity. They assumed a uniform velocity at the header inlet without considering the entrance effect. The flow distribution of trapezoidal shape is similar but is slightly worse than that of the triangular. For the rectangular header, the last tube has the highest flow rate, causing the flow mal-distribution. When the rectangular header was replaced with a triangular header, the flow distribution in the header was significantly improved.

Pretorius W.A. [18] demonstrated the use of a spread sheet program to calculate the hydraulics of a dividing-flow manifold. In this problem a (101.6 mm) diameter manifold divides a flow of (50.97 m^3/h) to (5) consecutive (50.8 mm) diameter short laterals. Each lateral is orientated at (90°) to the manifold and is square-edged. The task is to determine the flow distribution amongst the laterals. Depending on the assumption of Hudson et al. [19], which assume that the head loss in the energy line from manifold through lateral is the same at every point, the researcher present solution of the manifold-lateral system for two cases. In the first where a fixed sized manifold (the diameter of the manifold remain constant), the result shows that the discharge from lateral (1) is (56%) less than that from lateral (5). The second case is varying size manifold with constant lateral flow. In this case the diameter is reduced from (0.126 m) to (0.056 m) and produce an even discharge through (5) consecutive (0.051m) diameter laterals. Lu Hua [20] developed a computational model for the prediction of flow distribution in manifold type flow spreaders, several numerical techniques are used to address the difficulties associated with complex configurations of manifold type flow spreaders which can be found in many industrial applications, such that the manifold type flow spreader used in the head box in the paper-making system. The major effort in the work is to use and generalized multi- grid elliptic grid generation program to create grids for the tapered manifold spreader with different cross sectional configurations, especially for the manifolds with a circular cross section. The second step was to compute several two-and three-dimensional laminar and turbulent flows using CFD code to compared with other numerical, experimental and analytical results as a validation step to present computational method. A good agreement with literature results obtained for laminar flow distribution; also the effects of recirculation rate (flow out from manifold end) on the manifold flow distribution are studied. It is found that the flow rates from the downstream tubes drop dramatically with a (15%) recirculation rate, and that the zero recirculation rates causes high pressure and large flow rate from tubes near the manifold end.

Jones and Galliera [21] applied a Computational Fluid Dynamics (CFD) approach to predict 3-D steady flow and pressure fields in a T-junction coupled manifold with three risers, which consist of dividing and combining flow. Using standard and RNG k-s models in FLUENT to benchmark their integral model for flow distribution. They achieved good agreement between the two approaches and indicated that FLUENT can predict the large-scale features (e.g. distribution) of three-dimensional branching flows in a coupled manifold. Without including the quality effect, the application of single phase flow distribution study is still limited.

3. Factors for affecting the flow distribution

From the previously reported result of the cited references, the trends for the flow distribution affecting by several parameters are briefly discussed in the following. Commenge et al. [22] proposed a theoretical modeling approach in the form of an electrical resistance network to optimize the trapezoidal manifold geometry and obtain a uniform velocity distribution among microchannels. The calculation results were validated against numerical simulations. This approximate model establishes a relationship similar to Ohm's law between pressure drop, flow rate, and flow resistance. the losses in the manifolds (pressure losses due to merging and branching effects) are neglected, and only wall friction is considered. Therefore, the relationship established between pressure drop and flow rate is linear. Anjun et al. [23] investigated experimentally the effect of inlet header angle and mass flow rate on flow maldistribution to optimize the design of plate fin heat exchanger. The result showed that optimum performance can be obtained for an inlet angle of 45˚. Also, they found the inlet angle of the distributor to have negligible effects on pressure drop and were found to be dependent only on Reynolds number.

Zhe Zhang and Yan Zhong Li., [24] developed a computational model to predict the fluid flow distribution in plate-fin heat exchangers. It is found that the flow maldistribution is very serious in the y direction of header for the conventional header used in industry. The results of flow maldistribution are presented for a plate-fin heat exchanger, which is simulated according to the configuration of the plate-fin heat exchanger currently used in industry. The numerical prediction shows a good agreement with experimental measurement. By the investigation, two modified headers with a two-stage-distributing structure are proposed and simulated in this paper. The numerical investigation of the effects of the inlet equivalent diameters for the two-stage structures has been conducted and also compared with experimental measurement. It is verified that the fluid flow distribution in plate-fin heat exchangers is more uniform if the ratios of outlet and inlet equivalent diameters for both headers are equal. Jiao et al. [25] investigated experimentally the effect of the inlet pipe diameter, the first header's diameter of equivalent area and the second header's diameter of equivalent area on the flow maldistribution in plate-fin heat exchanger. For reducing flow maldistribution in the header, the authors were suggested modified header configuration. They installed a second header (B or C) after the first header to study the flow velocity distribution. The header configuration B has five holes in the connection part between the first and second headers while the header configuration C has seven holes. The flow velocity distribution of the configuration C gives the most uniform result among the cases considered in their paper. The flow distribution was effectively improved by the modified header configuration. Tonomura et al. [26] developed a computational model to optimize the rectangular manifold. Simulation results show that longer branched channels enable fluid to be distributed equally into each channel. Also demonstrated is the fact that the magnification of the outlet manifold area makes the flow distribution uniform. However, the extension of the outlet manifold increases dead volume inside the microdevice, broadens residence time distribution, and lengthens space time. The results of 2D and 3D CFD simulations on the flow distribution in microchannel structures with a triangular manifold have been compared by Griffini and Gavriilidis [27]. They concluded that for their study cases 2D simulations were correct because they gave an accurately the correct velocity distribution of flow required. Maharudrayya et al. [28] studied one dimensional models based on mass and momentum balance equations in the inlet and exhaust headers of U-type and Z-type parallel configurations having fuel cell applications. The models have been validated by comparing the results with those obtained from three-dimensional computational fluid dynamics (CFD) simulations. Their results showed that mild to severe flow maldistribution was possible in both the configurations for typical fuel-cell distributor plate dimensions. The severity of maldistribution depended strongly on the geometric factors such as the channel dimensions, the header dimensions and the rib width between parallel channels. Ramamurthy et al. [29] applied Reynolds averaged Navier-Stokes (RANS) equations to dividing flows in 90 deg rectangular conduit junctions. They adopted the Three -dimensional k-turbulence model for numerical simulation to obtain the dividing flow characteristics. These characteristics include the energy loss coefficients, pressure profiles, velocity profiles, and the mean flow pattern. The results are validated using experimental data. The experiment was carried out using The Dantec Laser Doppler Anemometry (LDA) to measure velocities in the test section. The zone of flow separation predicted by the model qualitatively agrees with the experimental data. They argued that their model can be used to obtain results such as energy loss coefficients for different area ratios and discharge ratios without too much effort. Wen et al. [30] investigated flow characteristics in the entrance region of plate-fin heat exchanger by means of particle image velocimetry (PIV). The experimental results indicate that flow maldistribution in the conventional header is very serious, while the improved header configuration with punched baffle can effectively improve the uniformity. The flow maldistribution parameter in plate-fin heat exchanger has been reduced from 1.21 to 0.21, and the ratio of the maximum velocity to the minimum is reduced from 23.2 to 1.8 by installing the punched baffle. Lu et al [31] formulated a discrete model for the calculation of flow distribution in flow manifolds from first principles. Experimental evaluation of flow characteristic parameters had been carried out to support the discrete model. Experiments were conducted to obtain the pressure distribution in the header under specific conditions. The validity of the theoretical discrete model has been performed with experimental results, under specific conditions. Refined experimental probes, for pressure heads with ultrasonic measuring devices, have been used to obtain accurate results. The experimental results fully substantiate the soundness of the theoretical prediction. In addition, the advantage of the ability to accommodate local disturbances in the discrete model has been pointed out. The effect of some local disturbances may be substantial. As a result of the analysis presented in this article, improved designs of flow manifolds in heat exchangers can be realized, to assure operation safety under severe operating conditions. Tong et al. [32] investigated numerically number of the strategies capable of perfecting manifold design to achieve the same rate of mass outflow through each of the exit ports of a distribution manifold. The results show that are most effective for the attainment of the goal of outflow uniformity, These are: (a) enlargement of the cross-sectional area of the distribution manifold, (b) variation of the cross-sectional areas of the outflow channels, (c) linear tapering of the cross-sectional area of the distribution manifold, and (d) non-linear tapering of the cross-sectional area of the manifold by means of quarter-elliptical contouring of the manifold wall.

Pan, Zeng, et al. [33] performed a three-dimensional computational fluid dynamics (CFD) model to calculate the velocity distribution among multiple parallel microchannels with triangle manifolds. The simulation results showed that the velocity distribution became more uniform with larger microchannel length, depth or smaller width. Larger horizontal ordinate, longitudinal ordinate and radius of inlet/outlet, smaller lengths of bottom and side of symmetrical manifolds could favor obtaining narrow velocity distribution among microchannels. The effect of channel width and channel spacing on flow distribution among microchannels with U-shape rectangular manifolds has been investigated by Mathew, John, and Hegab [34].

Andrew and Sparrow [35] present a method to investigate the effect of the geometric shape of the exit ports on mass flow rate uniformity effusing from a distribution manifold; three candidate exit-port geometries were considered: (a) an array of discrete slots, (b) an array of discrete circular apertures, and (c) a single continuous longitudinal rectangular slot. In order to have a valid comparison of the impacts of these individual geometries, the total exit areas of all three were made identical. The results of the per-port mass effusion normalized to the average mass-flow rate of the manifold demonstrate that the single continuous slot provides the best performance with end-to end variations of less than (±5%). The discrete array of rectangular slots and discrete array of circular holes provided uniformity of (±10%) and (±15%), respectively. Also it's found that the pressure rise for the various types of slot geometries is similar. Saber et al. [36] performed a model for rapid estimation of flow distribution in a complex network comprising several different scales under isothermal and laminar flow conditions. They found that a two-scale configuration of the flow distributor yielded the most uniform flow distribution. Tong et al. [37] applied a logic-based systematic method of designing manifold systems to achieve flow rate uniformity among the channels that interconnect a distribution manifold and a collection manifold. The method was based on tailoring the flow resistance of the individual channels to achieve equal pressure drops for all the channels. The tailoring of the flow resistance was accomplished by the use of gate-valve-like obstructions. Huang and Wang [38] examined an inverse design problem to determine the optimum variables for a three-dimensional Z-type compact parallel flow heat exchanger is with the Levenberg–Marquardt Method (LMM) [39] to obtain the uniform tube flow rates. Five different optimization design problems are examined to demonstrate the validity of the study. The results obtained from the LMM are justified based on numerical experiments. They concluded that the estimated optimal tube diameters and entrance length of the header can indeed effectively eliminate the eddy flow in the first tube due to the circulation of the vortex flow near the header inlet. As a result, the non-uniformity observed in the flow rate of the system can be minimized and the tube flow rate in the heat exchanger is nearly uniform. Wang et al. [40] investigated experimentally and numerically the single-phase flow into parallel flow heat exchangers with inlet and outlet rectangular headers having square cross section and nine circular tubes. The effects of inlet flow condition, tube diameter, header size, area ratio, flow directions (Z and U-type), as well as the gravity were investigated. The experimental results indicated that flow distribution for U-type flow is more uniform than Z-type flow. Depending on the inlet volumetric flow rate, the flow ratio of the first several tubes can be more than 50% lower than the last tube for the Z-type arrangement, a phenomenon becomes more and more pronounced with the rising velocity at the intake conduit.

In review article, Rebrov et al. [41] presented an experimental and numerical result on fluid flow distribution, heat transfer and combination thereof for microstructure reactors. They have given a special attention to the effect flow maldistribution on the thermal and conversion behavior of catalytic microreactors. Wang [42] presented experimentally the results of liquid flow distribution in compact parallel flow heat exchanger through a rectangular and 5 modified inlet headers (i.e., 1 trapezoidal, one multi-step, 2 baffle plates and 1 baffle tubes header). A jet stream induced at the header inlet associated with vortexes affecting the flow distribution to the front tubes. The flow distribution in the header highly depends on the header shape and the total flow rate. They concluded that the baffle tube has the best flow distribution since the vortex flow can be removed by using this header configuration. Wang [43] has examined research and development of theoretical models and methodology of solutions in flow in manifolds and highlight remarkable advances in the past fifty years. Author has reported three approaches: computational fluid dynamics (CFD), discrete models and analytical models. Further, author has reported three general characteristic parameters (E, M, ζ) which control the flow and pressure distribution in manifolds. Zeng, Pan, and Tang [44] performed a three-dimensional computational fluid dynamics (CFD) model to calculate the velocity distribution among microchannels with two different manifold structures. It was found that, as compared to the obtuse angled manifold, the right-angled manifold resulted in a more uniform flow distribution for all inlet velocities. A similar performance improvement with a more uniform flow distribution in methanol steam reformers was reported by Jang, Huang, and Cheng [45]. Such findings affirm the influence of flow distribution uniformity on the performance of microreactor devices and reflect the importance of efficient manifold design. Hanfei Tuo and Pega Hrnjak [46] investigation an experimentally and numerically the flow maldistribution caused by the pressure drop in headers and its impact on the performance of a microchannel evaporator with horizontal headers and vertically oriented tubes. Experimental results show that the flash gas bypass method almost eliminates the quality induced maldistribution. Nae-Hyun Kim and Ho-Won Byun [47] studied experimentally the effect of inlet configuration on upward branching of two-phase refrigerant in a parallel flow heat exchanger. Three different inlet orientations (parallel, normal, vertical) were investigated. The best flow distribution was obtained from vertical inlet configuration. Between other two inlet configurations, parallel inlet was better for liquid distribution, and normal inlet was better for gas distribution. Badar et al. [48] conducted a computational fluid dynamics (CFD) analysis to find the pressure losses for dividing and combining fluid flow through a tee junction of a solar collector manifold. The results were in reasonable agreement with the available experimental results for U-configuration. The proposed CFD based strategy can be used as a substitute to setting up and performing costly experiments for estimating junction losses.

4. Conclusion

In general, all previous studies with different applications have shown that typical manifold design does not give a uniform flow distribution among outlets. There will be a nonuniform mass flow distribution such that the smallest mass flowrate will occur in the outlet closest to the inlet and the highest flowrate will be encountered in the outlet farthest from the inlet. Correspondingly, the end-to-end pressure drops in the respective laterals will also be nonuniform. the cause as reported by several authors, the flow in the distribution manifold is gradually depleted as mass is extracted at each of the outlet. If the distribution manifold were to be uniform longitudinal section, the axial momentum would gradually decrease. This momentum decrease would give rise to an increase in the static pressure. Such an increase in static pressure should favor a higher efflux through the downstream outlets. In this article, a comprehensive review of previous efforts was presented for different flow distribution regimes. there are several approaches used by different research groups to achieve flow uniformity in manifolds. The issue of flow equalization is usually adequately tackled by using 3D numerical models. 2D CFD models could not adequately predict flow distribution in flow distribution manifolds. The effects of several parameters in geometry, boundary conditions, stream velocity in the header (or manifold), size of the header, diameter of the parallel channels, location and size of inlet port to the header, flow direction, operating conditions and fluid properties were extensively investigated to improve the uniformity degree of flow distribution.

Reference

[1] Jimmy c. k. tong, development of systematic solution methodologies for the fluid-flow manifold problem, University of Minnesota, Ph.D. Dissertation, 2006.
[2] McNown, J.S. “Mechanics of manifold flow” Transactions of ASCE, 119. pp. 1103-1142, 1954.
[3] Acrivos, A., Babcock, B.D., Pigford,R.L. “Flow distributions in manifolds” Chemical Engineering Science, 10. pp. 112-124,1959.
[4] Pigford, R.L., Ashraf, M., Mlron, Y.D. (1983). Flow distribution in piping manifolds. Ind. Eng. Chem. Fundam. 22. pp. 463–471.
[5] M. S. Gandhia, at al. “ CFD simulation for steam distribution in header and tube assemblies ” chemical engineering research and design 90 (2012) 487-506
[6] Bajura, R. A. “A model for flow distribution in manifolds,” Journal of Engineering for Power-Transactions ASME, 1971, Vol. 93, No. 1, pp. 7-12.
[7] Bajura, R. A. and E. H. Jones, , “Flow distribution manifolds,” Journal o f Fluids Engineering-Transactions ASME, 1976, Vol. 98, No. 4, pp. 654-666.
[8] Majumdar, A.K., “Mathematical modelling of flows in dividing and combining flow manifold” Appl. Math. Model. 4 (1984) 424–432.
[9] Datta, A.B., Majumdar, A.K. “Flow distribution in parallel and reverse flow manifolds” Int. J. Heat Fluid Flow 2 (1980) 253–262.
[10] Pigford, R.L., Asharf, M., Miron, Y.D., “Flow distribution in piping manifolds” Ind. Eng. Chem. Fundam. 22 (1983) 463–471.
[11] Bassiouny, M.K., Martin, H., “Flow distribution and pressure drop in plate heat exchangers-I U-type arrangement” Chem. Eng. Sci. 39 (1984) 693–700.
[12] Bassiouny, M.K., Martin, H., “Flow distribution and pressure drop in plate heat exchangers-II Z-type arrangement” Chem. Eng. Sci. 39 (1984) 701–704.
[13] Mueller, A.C., Chiou, J.P., “Review of various types of flow maldistribution in heat exchangers” Heat Trans. Eng. 5 (1988) 36–50.
[14] Shen P. I., “The Effect of Friction on Flow Distribution in Dividing and Combining Flow Manifold” Transaction of the ASME, J. of Fluids Engineering, vol. 114, 1992.
[15] Choi, S. H., Shin, S. and Cho, Y. I., "The effect of area ratio on the flow distribution in liquid cooling module manifolds for electronic packaging," Int. Comm. Heat Mass Transfer, 20, (1993) 221-234.
[16] Choi, S. H., Shin, S. and Cho, Y. I., "The effect of Reynolds number and width ratio on the flow distribution of liquid cooling module manifolds for electronic packaging," Int. Comm. Heat Mass Transfer, 20 (1993) 607-617.
[17] S. Kim, E. Choi, Y.I. Cho, “The effect of header shapes on the flow distribution in a manifold for electronic packaging applications” International Communications in Heat and Mass Transfer 22 (1995) 329-341.

[18] Pertorius W.A., “Dividing- flow Manifold Calculations with a Spreadsheet”, water science, vol. 23, No. 2, 1997.
[19] Hudson, H.E. et al., “Dividing-Flow Manifolds with Square-Edged Laterals”, Journal of the Environmental Engineering Division, (745-754) 1979.
[20] Lu Hua, “Computational Modeling of Manifold Type Flowspreaders”, MSc Thesis, the University of Columbia, 1998.
[21] Jones, G. F. and J. M. Galliera, , “Isothermal flow distribution in coupled manifolds: Comparison o f results from CFD and an integral model” Americtm Society of Mechanical Engineers, Fluids Engineering Division, Fairfield, NJ, 247 (1998) 189-195.
[22] Commenge, J., Falk, L., Corriou, J. P., & Matlosz, M. Optimal design for flow uniformity in microchannel reactors. AICHE Journal, 48 (2002) 345–358.
[23] Anjun, J., Yanzhong, L., ChunZheng, C., and Rui, Z., “Experimental Investigation on Fluid Flow Maldistribution in Plate-Fin Heat Exchangers’’ Heat Transfer Engineering, 24 (2003) 25-31.
[24] Zhe Zhang and YanZhong Li., “CFD simulation on inlet configuration of plate-fin heat exchangers” Cryogenics 43 (2003) 673–678.
[25] A. Jiao, R. Zhang, S. Jeong, “Experimental investigation of header configuration on flow mal-distribution in plate-fin heat exchanger” Applied Thermal Engineering 23 (2003) 1235-1246.
[26] Tonomura, O., Tanaka, S., Noda, M., Kano, M., Hasebe, S., & Hashimoto, L. “CFD based optimal design of manifold in plate-fin microdevices” Chemical Engineering Journal, 101(2004) 397-402.
[27] Griffini, G., & Gavriilidis, A. “Effect of microchannel plate design on fluid flow uniformity at low flow rates” Chem. Engineering & Technology 30 (2007) 395-406.
[28] Maharudrayya, S., Jayanti, S., and Deshpande, A. P., “Flow distribution and pressure drop in parallelchanne configurations of planar fuel cells’’ Journal of Power Sources, vol. 144 (2005) 94-106.
[29] Ramamurthy A. S., Junying Qu, Diep Vo, Chao Zhai, “3-D Simulation of Dividing Flows in 90 deg Rectangular Closed Conduits”, Transactions of the ASME, J. of Fluids Engineering, Vol. 128, 2006.
[30] Wen, J., Li, Y., Zhou, A., Ma, Y.,P “IV investigations of flow patterns in the entrance configuration of plate-fin heat exchanger” Chin. J. Chem. Eng. 14 (2006) 15–23.
[31] LU Fang, LUO Yong-hao and YANG Shi-ming. “Analytical and experimental investigation of flow distribution in manifolds for heat exchangers”. Journal of Hydrodynamics, 20(2) (2008)179-185.
[32] J.C.K. Tong, E.M. Sparrow, J.P. Abraham, Geometric strategies for attainment of identical outflows through all of the exit ports of a distribution manifold in a manifold system, Applied Thermal Eng. 29 (2009) 3552-3560.
[33] Pan, M., Zeng, D., Tang, Y., & Chen, D. “CFD-based study of velocity distribution among multiple parallel microchannels” J. of Computers, 4 (2009) 1133–1138.
[34] Mathew, B., John, T. J., & Hegab, H. “Effect of manifold design on flow distribution in multichanneled microfluidic devices” ASME Fluids Engineering Division Summer Conference, FEDSM 2009, Vol. 2, pp. 543–548.
[35] Andrew W. Chen, Ephraim M. Sparrow, “Effect of Exit-port Geometry on the Performance of a Flow Distribution Manifold”, Applied Thermal Engineering, 29 (2009) pp. 2689-2692.
[36] Saber, M., Commenge, J., Falk, L., “Rapid design of channel multi-scale networks with minimum flow mal-distribution” Chem. Eng. Process, 48 (2009) 723–733.
[37] J.C.K. Tong, E.M. Sparrow, J.P. Abraham, Attainment of flowrate uniformity in the channels that link a distribution manifold to a collection manifold, J. Fluids Eng. 129 (2007) 1186–1192.
[38] C.H. Huang, C.H. Wang, “The design of uniform tube flow rates for Z-type compact parallel flow heat exchangers” Int. J. Heat Mass Transfer (SCI&EI paper) 57 (2013) 608–622.
[39] D.M. Marquardt, “An algorithm for least-squares estimation of nonlinear parameters”, J. Soc. Ind. Appl. Math. 11 (1963) 431–441.
[40] C.C. Wang, K.S. Yang, J.S. Tsai, I.Y. Chen, Characteristics of flow distribution in compact parallel flow heat exchangers, part I: typical inlet header, Appl. Therm. Eng. 31 (2011) 3226–3234.
[41] Rebrov, E.V., Schouten, J.C., de Croon, M., “Single-phase fluid flow distribution and heat transfer in microstructured reactors”, Chem. Eng. Sci. 66 (2011) 1374–1393.
[42] C.C. Wang, K.S. Yang, J.S. Tsai, I.Y. Chen, “Characteristics of flow distribution in compact parallel flow heat exchangers, Part II: Modified inlet header”, Appl. Thermal Eng. 31 (2011) 3235–3242.
[43] Wang, J., “Theory of flow distribution in manifolds”, Chem. Eng. J. 168 (2011) 1331–1345.
[44] Zeng, D., Pan, M., & Tang, Y. Qualitative investigation on effects of manifold shape on methanol steam reforming for hydrogen production. Renewable Energy, 39 (2012) 313–322.
[45] Jang, J.-Y., Huang, Y.-X., & Cheng, C.-H. “The effects of geometric and operating conditions on the hydrogen production performance of a micro-methanol steam reformer”, Chem. Eng. Science, 65 (2010). 5495–5506.
[46] Hanfei Tuo a, Pega Hrnjak “Effect of the header pressure drop induced flow maldistribution on the microchannel evaporator performance”, international journal of refrigeration 36 (2013) 2176-2186.
[47] Nae-Hyun Kim and Ho-Won Byun, “ Effect of inlet configuration on upward branching of two-phase refrigerant in a parallel flow heat exchanger” int. j. of refrigeration 36 (2013) 1062-1077.
[48] Badar et al., “CFD based analysis of flow distribution in a coaxial vacuum tube solar collector with laminar flow conditions, International Journal of Energy and Environmental Engineering 2012, http://www.journal-ijeee.com/content/3/1/24