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Study of Three Dimensional Fluid Flow in Manifold-Laterals System

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ABSTRACT

A three dimensional numerical simulation of fluid flow in a manifold-laterals system was carried out; several geometrical changes were made to study the effect on water flowing inside the manifold. The manifold hydraulic diameter and the length were kept constant in the study. The geometrical changes include the distance between laterals, the length of the laterals, and the laterals size. It is found that for Reynolds Number (100 and 1000), increasing the length of the laterals gives uniform flow profile at laterals outlet. Also reducing lateral size will create a similar effect. A good agreement was found between the present and FLUENT6.2 results for mass flow rate from laterals.

Keywords: manifold flow, lateral length, CFD, uniform outflow.

دراسة الجريان ثلاثي الابعاد في نظام الانبوب المتعدد التفرعات

الخلاصة

تم اجراء دراسة عددية ثلاثية الابعاد لجريان مائع داخل انبوب ذات تفرعات متعددة. تم دراسة تاثير العديد من التغييرات للشكل الهندسي للانبوب على جريان الماء داخل الانبوب. تم تثبيت القطر الهيدروليكي للانبوب وطوله في هذه الدراسة. تضمنت التغييرات في الشكل، المسافة بين التفرعات، طول التفرعات، وحجم التفرع. لقد وجد عند ارقام رينولدز (100 و1000) بان زيادة طول التفرع يجعل جريان الماء منتظما عند مخارج التفرعات. كذلك بتغيير حجم التفرعات يمكن الحصول على نفس النتيجة مع ثبوت الابعاد الاخرى. بالمقارنة مع برنامج (فلونت 6.2) تم الحصول على تقارب جيد مع نتائج الدراسة الحالية فيما يخص معدل التدفق الكتلي الخارج من جميع التفرعات.

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List of symbol

B	Distance between laterals	m
D	Hydraulic Diameter	m
h_L	head difference between first and last lateral	—
H	The length of the laterals	m
L	Manifold length	m
M	discharge ratio of first to the last lateral	—
P	Dimensionless pressure	—
Re	Reynolds Number	—
S	Lateral size	m
S_u,S_P	Source Terms in eq. (5)	—
U,V,W	Dimensionless velocities in X,Y,Z-directions	—
u, v, w	velocities in x,y,z-directions	m/s
u_{in}	Inlet velocity	m/s
X,Y,Z	Cartesian coordinates	—
ρ	Density of the fluid (water)	kg/m^3
ϕ	General variable in eq. (5)	—

Abbreviations

LDA	Laser Doppler Anemometry
RANS	Reynolds Averaged Navier-Stokes
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations

INTRODUCTION

Dividing flow manifold are often used in water and wastewater treatment plants and many other industrial applications, such as heat exchanger, pipe burners, irrigation system, chemical-processing equipment such as contactors, reactors, mixers, extrusion dies, and textile-spinning chimneys. Manifold-lateral system is also essential in paper machine hydraulic head boxes. Manifolds may be classified into two categories. One of these categories is distribution manifolds, wherein there is a single inlet and multiple exits. The other category is collection manifolds, where there are multiple inlets and a single exit. A major goal of manifold design is the attainment of flow uniformity at the multiple exits of a distribution manifold. In systems consisting of both a distribution manifold and a collection manifold, the design goal is to achieve an identical rate of flow in each of the channels that link the exits of the distribution manifold to the inlets of the collection manifold.

A numerous analytical and experimental works has been done to describe the characteristics and flow behavior in a divided manifold, Hudson et al. [1] present a method of analysis for dividing-flow junction losses based on correlation of numerous data sets, and by given examples they describe the use of the analytical procedure to evaluate dividing manifold problems. They study two types of manifold (circular manifold), short and long lateral manifold. Where short lateral manifold is that one which has laterals with length less than three pipe diameter and long laterals manifold are greater than three pipe diameter in length. It is concluded that the entry loss coefficients for laterals discharging from a dividing flow manifold bear linear relationship to the squares of the ratios of manifold-to-lateral velocities. Also the entry loss coefficients for short laterals are larger than those for long laterals manifold due to partial recovery of the velocity head in the later which leads to a more uniform velocity profile in long manifold.

Benefild et al. [2] gave a study of dividing flow manifolds that is used in environmental engineering, this kind of manifold distribute flow uniformly across the size of one or several treatment units (three parallel rectangular sedimentation basins). They define two variables (M & h_L) where (M is the ratio of first lateral discharge to the last lateral discharge) and (h_L is the difference in head available to the first lateral and the last lateral). They suggest that one of two situations can exist in a dividing-flow manifold system,

1- The manifold may be quite small so that the head loss due to friction along the manifold is large. In this case the flow through the first lateral will probably be greater than the flow through the last lateral so (h_L) will be positive, and (M) will have a value greater than unity.

2- The manifold may be quite large so that the head loss due to friction along the manifold is small. In this case velocity head recovery occurs along the manifold due to decreasing flow rate. Thus, the pressure will be greater at the downstream end of the manifold and this will result in a higher flow through the last lateral than through the first one. The (h_L) will be negative and (M) will have a value less than unity.

Shen, P.I. [3] give 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, (α) (the friction parameter) and (β) (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.

Pretorius W.A. [4] 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^o) 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. [1], which assume that the head loss in the energy line from manifold through lateral is the same at every point, the researcher present a 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 (0.126m) to (0.056m) and produce an even discharge through (5) consecutive (0.051m) diameter laterals.

Kenji et al. [5] presents an experimental study to determine energy loss coefficients for smooth, sharp-edged tees of circular cross-section with large area ratio. By using equations developed from the continuity, energy, and momentum principles they expressed the loss coefficients with correspond correction factors needed in the equations. The comparison of the proposed equations with the experimental results obtained by others shows that the proposed equations, with the correction factors gave good agreement with the experimental results for the area ratio greater than 8. The experiments were carried out with ($Re=10^5$) for the branch pipe and ($3*10^4$) for the main pipe, while the branch angles ranged from (45^o to 135^o).

In (2006), Ramamurthy et al. [6] 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.

Lu Hua [7], 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 which consider as a critical component in the system.

The major effort in the work is to use and generalized multigrid 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.

Andrew and Sparrow [8], 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.

The present study handled a laminar case of water flowing in a manifold lateral system. A case that mostly found in several engineering applications, such as chemical processing system and water power station (refining). In such system it is important to have a uniform outlet flow from laterals to prevent unbalance pumping. The aim is to build and test a numerical procedure to solve the governing equations of continuity and momentum in such 3-D complex geometry and to study the effect of several geometrical arrangements on the flow distribution in the lateral outlets.

PHYSICAL AND MATHEMATICAL MODEL

Considering a steady, three-dimensional laminar water flow in the manifold shown in Fig. (1) with end of the manifold is closed.The inlet hydraulic diameter is (D). It is assume that all remaining geometrical dimensions depend on (D). The size (S), height (H) and the distance between laterals (B) will be changed to study their effect on flow in the dividing manifold. Body forces and viscous dissipation are assumed to be negligible. The equations governing continuity and momentum can be expressed in the following non-dimensional form [9]:

Conservation of Mass:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}+\frac{\partial W}{\partial Z}=0 \qquad \dots (1)$$

Conservation of Momentum:

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}+W\frac{\partial U}{\partial Z}=-\frac{\partial P}{\partial X}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}+\frac{\partial^2 U}{\partial Z^2}\right) \qquad \dots (2)$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}+W\frac{\partial V}{\partial Z}=-\frac{\partial P}{\partial Y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}+\frac{\partial^2 V}{\partial Z^2}\right) \qquad \dots (3)$$

$$U\frac{\partial W}{\partial X}+V\frac{\partial W}{\partial Y}+W\frac{\partial W}{\partial Z}=-\frac{\partial P}{\partial Z}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 W}{\partial X^2}+\frac{\partial^2 W}{\partial Y^2}+\frac{\partial^2 W}{\partial Z^2}\right) \qquad \ldots(4)$$

Where

$$X=\frac{x}{D} \qquad Y=\frac{y}{D} \qquad Z=\frac{z}{D}$$

$$U=\frac{u}{u_{in}} \qquad V=\frac{v}{u_{in}} \qquad W=\frac{w}{u_{in}}$$

$$P=\frac{p}{r u_{in}^{2}}$$

Referring to Fig. (1) The boundary conditions are:

- At inlet:

  U= 1.0, V=W= 0
- At walls:
  No slip condition is assumed.
  U= V= W= 0
- At lateral outlets:

$$\frac{\partial U}{\partial Y}=\frac{\partial V}{\partial Y}=\frac{\partial W}{\partial Y}=0$$

METHOD OF SOLUTION

The finite-volume technique is used, which combines features of the SIMPLE with a whole field pressure correction algorithm [10].

The basic idea of the SIMPLE algorithm is (i) to assume an artificial link between the cell-centered pressure and the cell-face velocities from the discretised momentum equations, (ii) to frame a system of linear equations for pressure correction that satisfy continuity and (iii) finally to correct the pressure and velocities accordingly [10].
The discretisation of U, V, and W- momentum equations can be written as [11]:

$$(\Sigma \mathrm{A_i}-\mathrm{S_p})\varphi_{\mathrm{p}}=\Sigma(\mathrm{A_i}\varphi_{\mathrm{i}})+\mathrm{S_u} \qquad \ldots(5)$$

Where : (φ) is a general variable such that ($\varphi = 1$) for continuity and (φ = U, V, W) for momentum.
(S_u, S_p) is source terms contain the pressure, body forces …etc.

The above equation was solved for the three velocity components and a pressure correction equation for each nodal point using an iterative solution with under relaxation factor of (0.5) for all variable to stabiles the solution. A novel treatment in the iterative procedure is used to handle the complicated domain. It is as follow:

1. The manifold domain is solved first for U velocity component.
2. Then the lateral domains were then solved for U velocity component.
3. Similarly V and W components were solved for manifold and then lateral fields.
4. Finally the pressure correction equation was solved for manifold and laterals as one field.
5. The velocity components and pressure were then corrected respectively.

The above steps are repeated iteratively until a convergence criterion for continuity of (10^{-5}) is reached. Fig. (2) Shows the flowchart of the program that used in this paper.

RESULTS AND DISCUSSION

The results of fluid flow in manifold- laterals system having constant length (L=9D) are firstly validated as shown in Fig. (3) and then presented according to the following cases:

1- The distance between laterals are taken (B=D, 0.5D, 0.25D) for (Re =100, 1000) as in Fig. (4).
2- The length of the laterals (H=2D, 4D, 6D) as in Fig. (5).
3- The lateral size (S= 0.5D, 0.25D) as in Figs. (6, 7, and 8).

The validation of the numerical simulation was done by comparing the present results with the results of FLUENT6.2 for the same geometry, grid, and boundary conditions. Fig. (3) Shows the comparison of the mass flow rate for both cases. The distance between laterals was (B=D), the length of laterals was (H=2D), the lateral size (S=0.5D), and (Re= 1000), Fig. (3) Shows a good agreement with a differences not exceed (4%).

After the validation of the computer program, it is applied to solve several cases starting with Fig. (4). the dominant velocities in the manifold and the laterals are plotted in figs. (4-a) to (4-f) (i.e. the U velocity component in the manifold and the V velocity component in the laterals) and for more detail values for the resultant velocities of the three components see the vector plots (Fig. (5)). Fig. (4) Shows the velocity and pressure contours at (H=2D) and (S=0.5D) along the symmetry plane. Fig. (4-a, b, and c) represent the effect of decreasing of (B) on the velocity contour at Reynolds number (Re=100). The zone of higher velocity steps forward along the manifold which increases the recirculation flow in the lateral. Also this leads to reduce the flow rate at the first lateral and increase it at the last. The effects of (Re) variation for the same distance i.e. Fig. (4-a) and Fig. (4-d) increases the recirculation of flow at the lateral and the dead zone (end of manifold) due to increase the velocities. Fig. (4-g to 4-l) shows the variation of pressure contour at different (B) for (Re=100, 1000), the pressure is reduced according to the variation of velocity. Except of the zone at the inlet of the lateral where it is increased due to recirculation.

The effect of lateral length (H) on the velocity is shown in Fig. (5). It can be seen that the velocity vector at the outlet becomes more uniform due to increase the length of the lateral which is agreed with results describe by Hudson [1].

The effect of velocity vector as a function of (S) is shown in Fig. (6). It is found that the velocity vector become uniform at the outlet of the lateral for the same length when the size of the lateral is reduced. Fig. (7) Shows the effect of (S) on mass flow rate out from the laterals, it is shown from the bar chart that the mass flow rate become uniform when reducing the (S) value to (S=0.25D) as shown in Fig. (8) . The effect of variation of (S) on velocity and pressure contour are shown in Fig. (9), in this figure for (Re=100 and 1000) the reverse flow region at higher lateral size is diminished when (S) is reduced, also the pressure was decreased in the manifold by reducing the size according to increase in velocity. This is agreed with Kyoungwoo Park [12].

The optimum design of pumping units depends on factors (H, S) and the distance between laterals (B), as shown in Fig. (5) and (6). The good compromise of (H, S, and B) will prevent the probability of cavitation occurrence at the inlet of the pump that leads to damage the system. The relation between the mass flow rate for different (H, S, and B) at (Re=1000) is shown in Fig. (7). It is found that the percentage difference of mass flow rate between the first and last lateral will change according to dimensions of (H, S, and B). Reducing (B) when (S=0.5D) will change the percentage difference from (9%) to (13%) which means that Fig. (7- c) is better where the difference is reduced by (13%). When (S=0.25D) the reduction of (B) will also effect on the percentage difference in mass flow rate, it will change from (4% to 6%) at Fig. (7-c). Therefore Fig. (7-c) is the best in preventing the probability of cavitation occurrence. i.e. (H=6D, B=0.25D, and S=0.5D, 0.25D) . The effect of the parameter (S) is shown also as a bar plot in Fig. (8) and Fig.(9) . The five bars represent the five laterals plotted along the manifold axis and the length of each bar represent mass flow rate in (kg/s) . It is clear that Fig. (9) with (S=0.25 D) shows approximately similar mass flow rates for the five laterals .

CONCLUSIONS

1. Decreasing the distance between laterals has a little effect on the flow and pressure fields at low Reynolds number, the effect will be clear at (Re=1000).
2. The flow profiles change to a uniform profile as the length of the laterals increase three times the manifold diameter (D).
3. At short manifold (H =2D), decreasing the lateral size to the half of the original will change the profile at the exit ports to uniform by reducing the recirculation in the laterals.
4. Decreasing the laterals size will decrease the difference in the mass flow rates between the laterals at the same Reynolds number.
5. The optimum design of any system could be found by using a good compromise of (H, S, and B).

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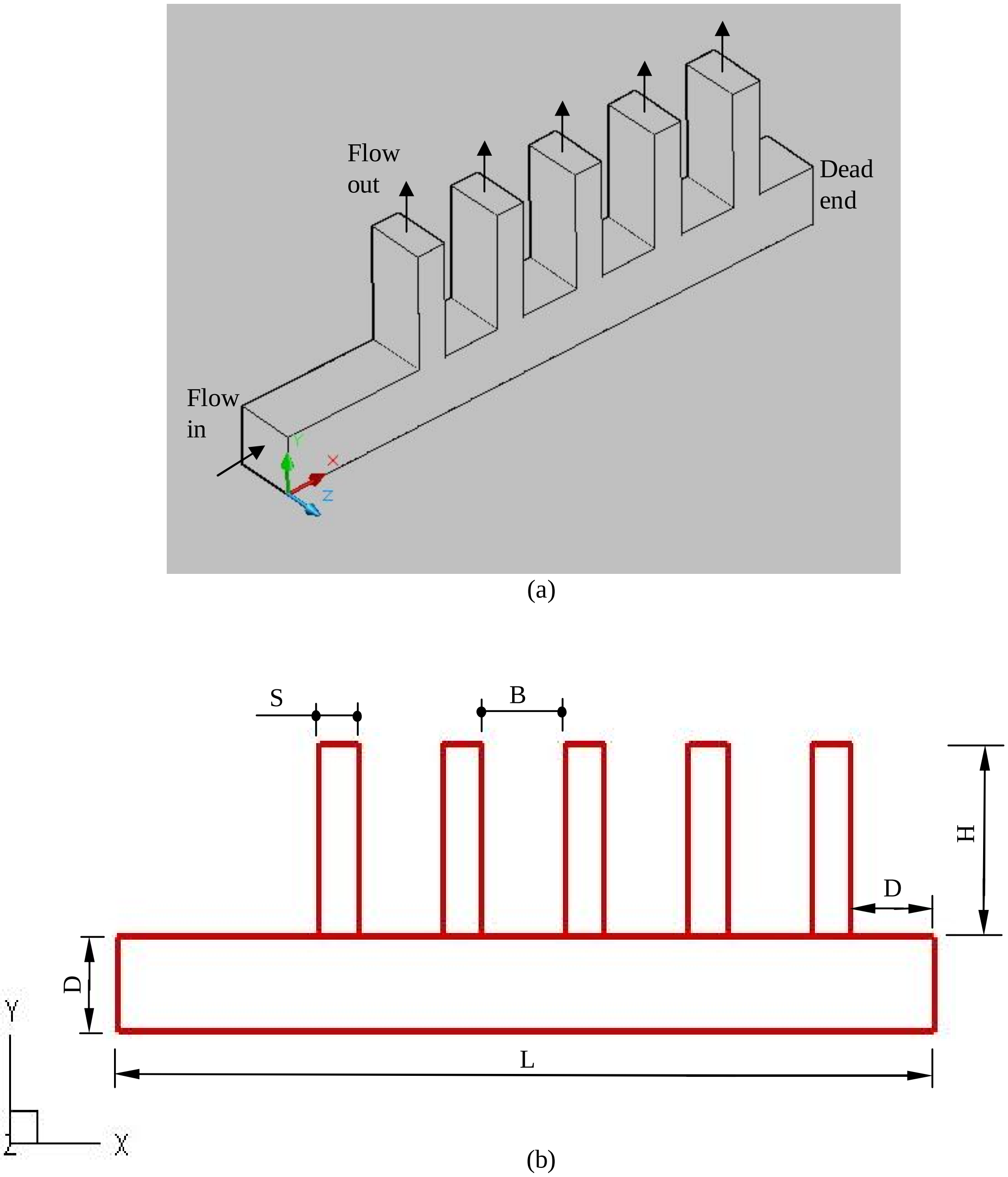


(a)

(b)

Figure (1) Schematic of the Manifold- laterals system.
(a) Isometric view, (b) Symmetry plane across the manifold.

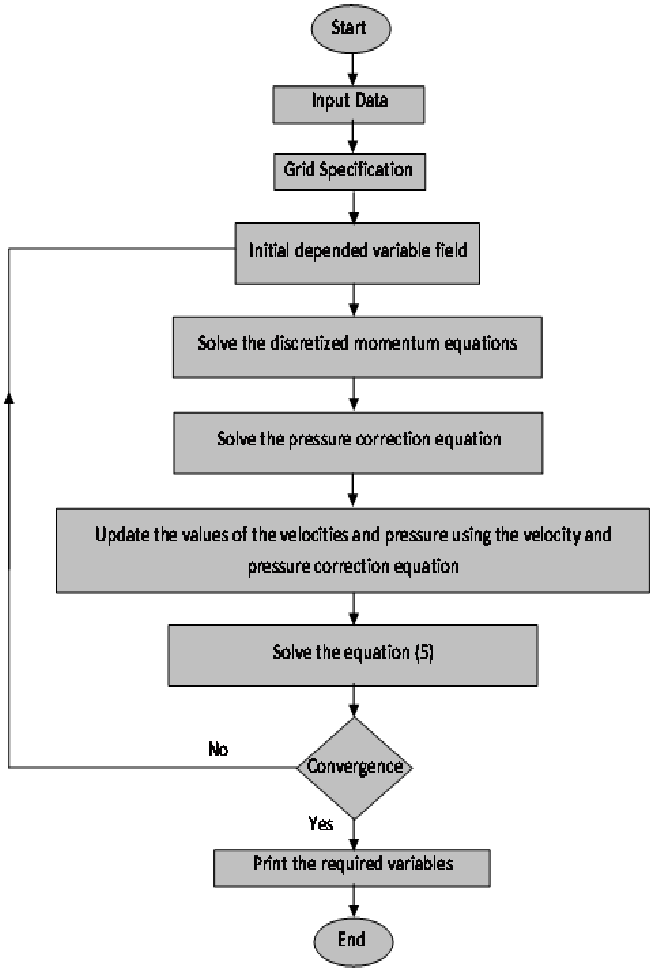


Figure (2) Flowchart of the numerical program

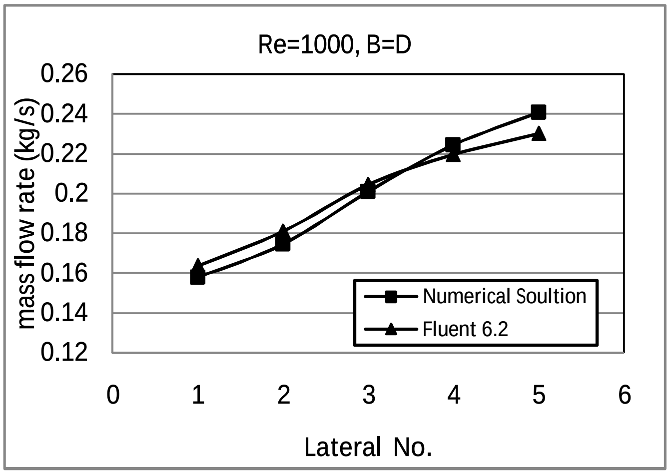
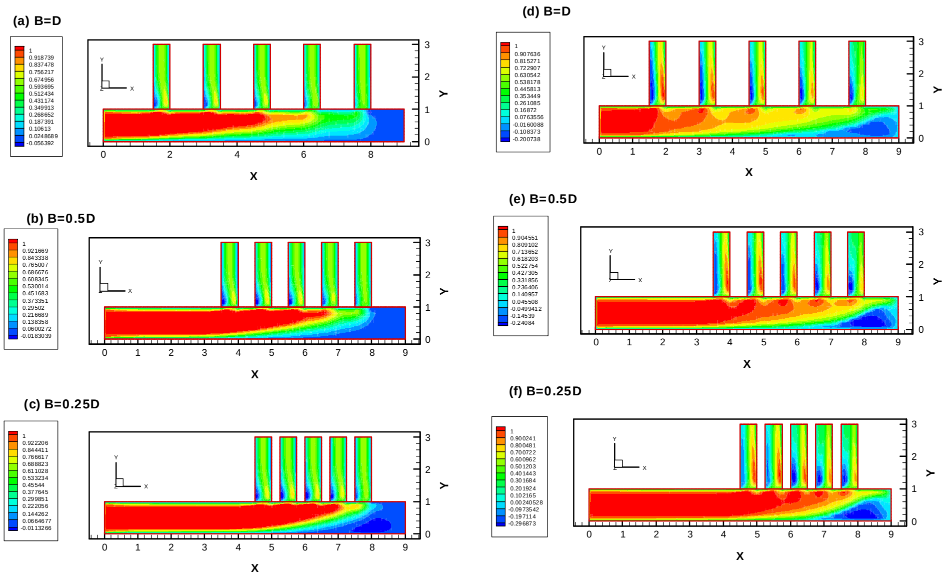
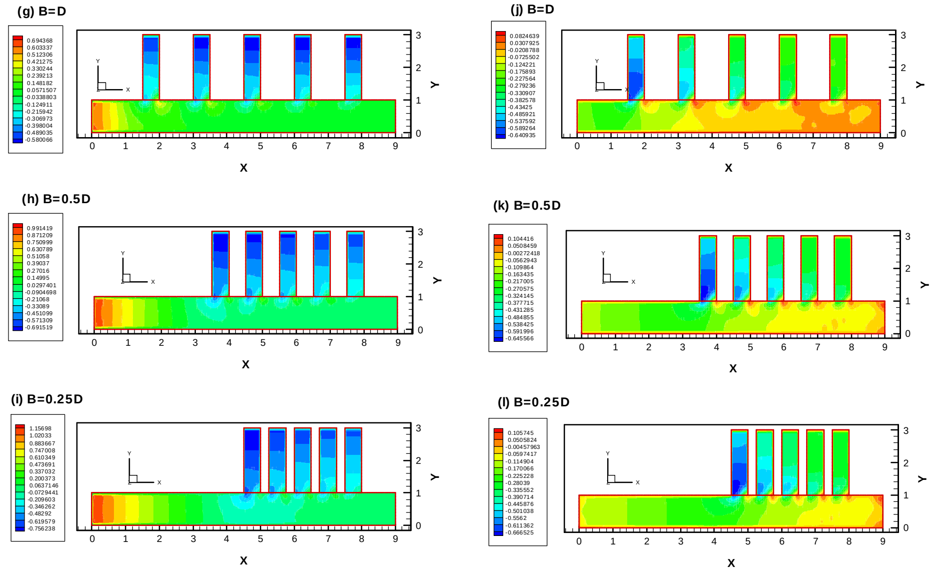


Figure (3) Effect of distance between lateral (B) on velocity and pressure contours at (H=2D,S=0.5D)


(a) B=D
(b) B=0.5D
(c) B=0.25D
(d) B=D
(e) B=0.5D
(f) B=0.25D

Re=100 (Velocity)

Re=1000 (Velocity)


(g) B=D
(h) B=0.5D
(i) B=0.25D
(j) B=D
(k) B=0.5D
(l) B=0.25D

Re=100 (Pressure)

Re=1000 (Pressure)

Figure (4) Effect of distance between laterals (B) on the velocity and Pressure Contour at (H=2D, S=0.5S)

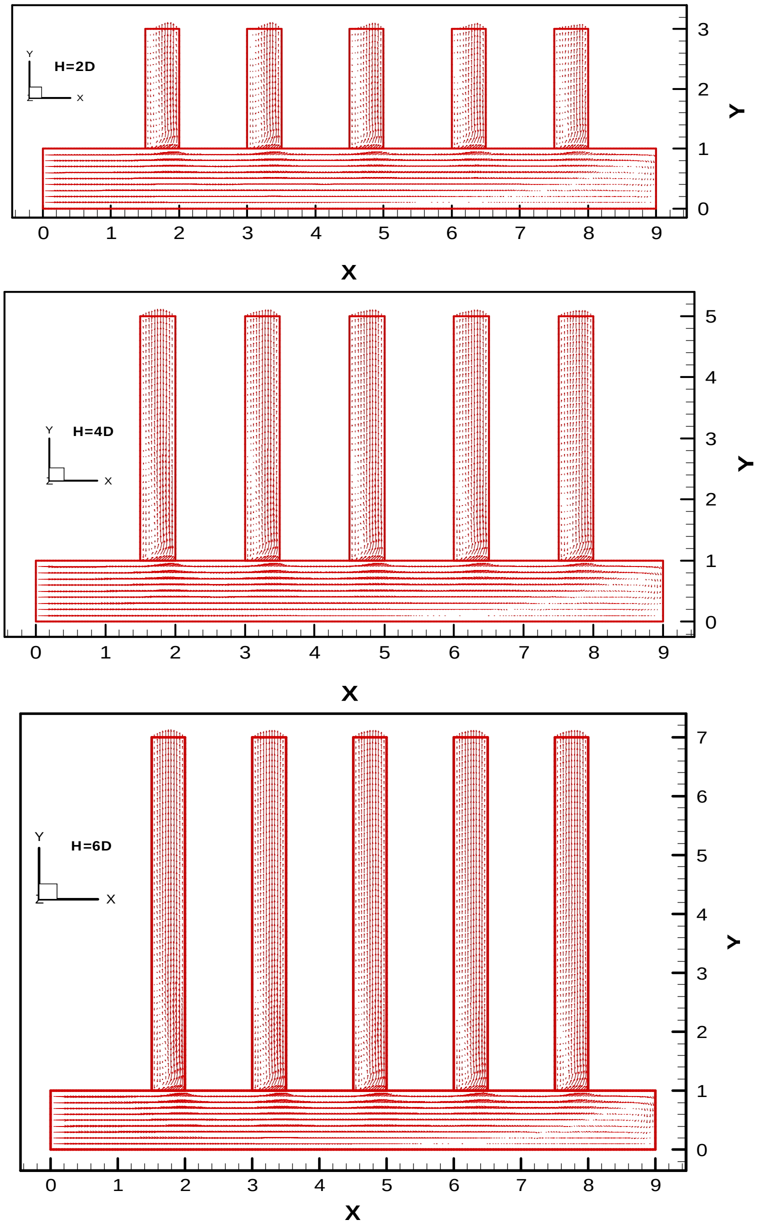
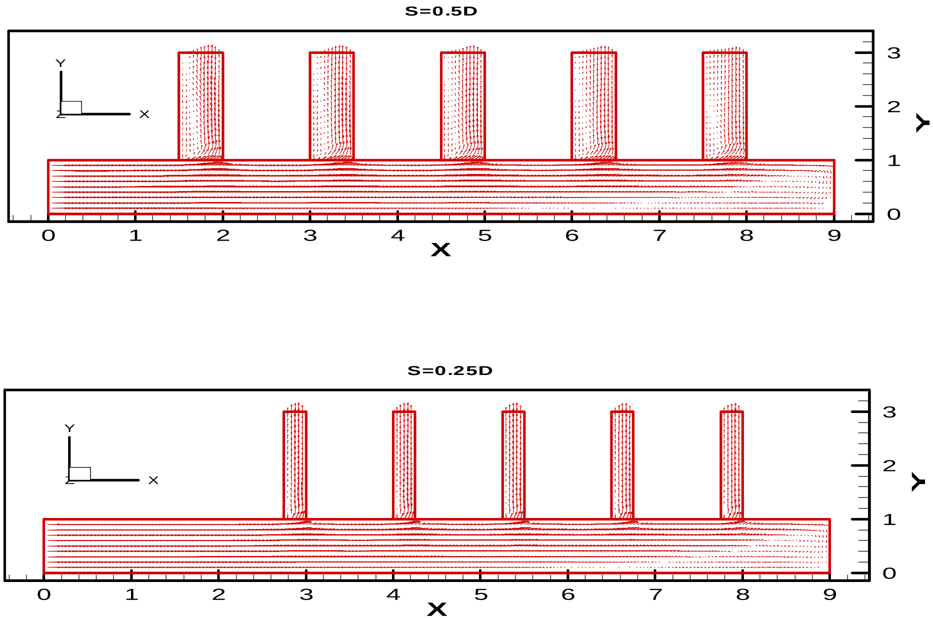
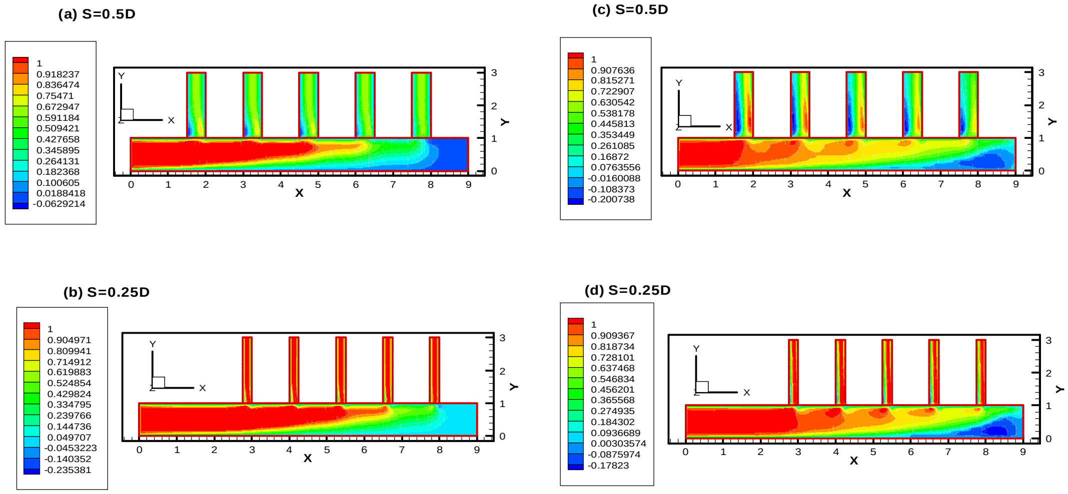


Figure (5) Effect of lateral (H) on the velocity vector at (S=0.5D ,B=D, and Re= 1000)


S=0.5D

S=0.25D

Figure (6) Effect of lateral size (S) on velocity Vector at (H=2D, B=D,and Re=1000)


(a) S=0.5D

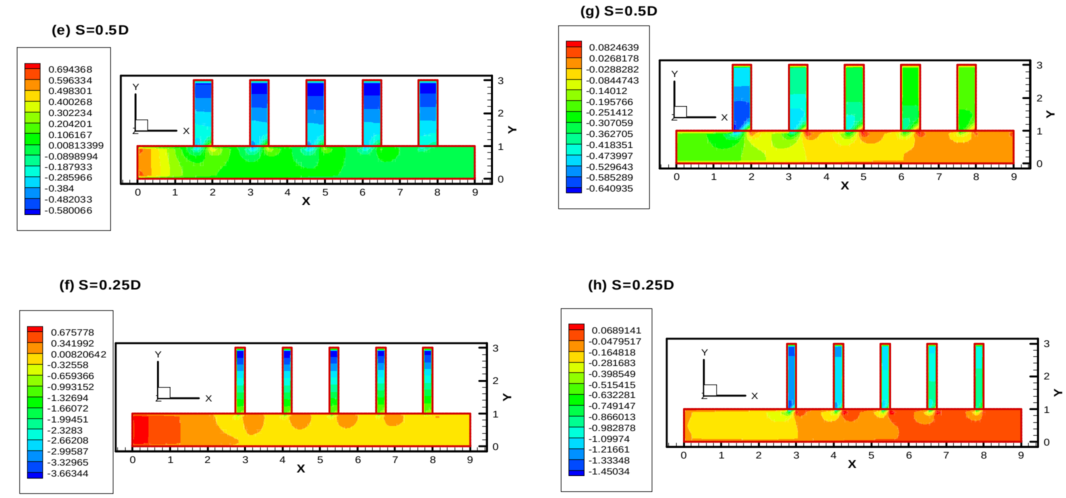
(b) S=0.25D

(c) S=0.5D

(d) S=0.25D

Re= 100 (Velocity)

Re= 1000 (Velocity)


(e) S=0.5D

(f) S=0.25D

(g) S=0.5D

(h) S=0.25D

Re= 100 (Pressure)

Re= 1000 (Pressure)

Figure (7) effect of lateral size (s) on Mass flow rate at (H=2D,B=D, and Re=1000)

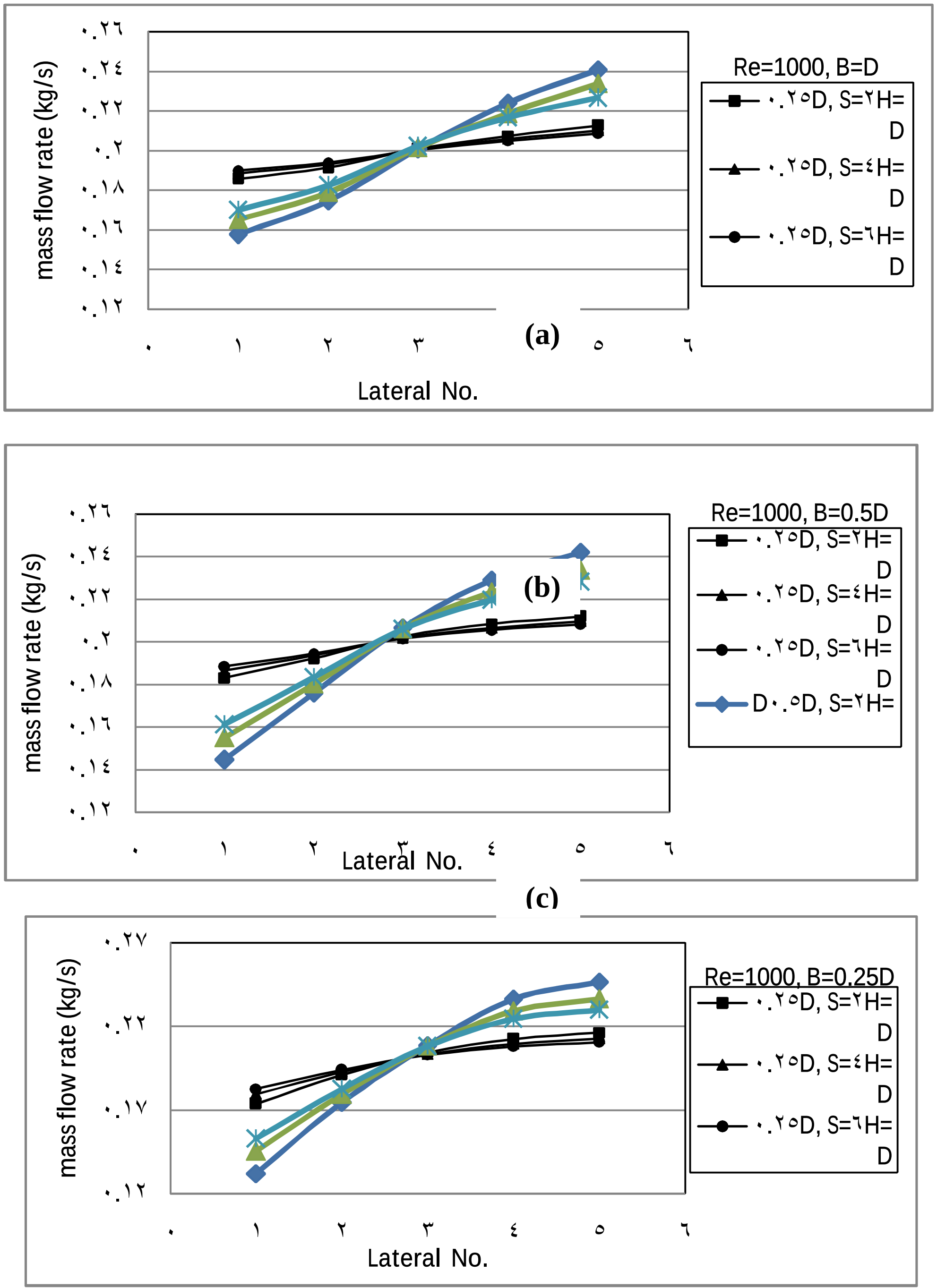


Figure (8) Mass flow rate variation for S=0.5D and Re=1000.