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NUMERICAL INVESTIGATION OF MULTI-CHANNEL FLOW MALDISTRIBUTION

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ABSTRACT

Non-uniform flow distribution is a very common problem which is encountered by process equipment designers. Being important design parameters, it has been investigated by several researchers and case based solution has been proposed and documented. Present numerical work is intended to target this aspect of the problem. The numerical setup consists of two headers having multiple channels for U and Z turn flow configuration. For hydrodynamic study, flow has been varied for Reynolds number 120 to 17600 to study the effect of flow behaviour on mal-distribution. It has been found that channel flow goes on reducing along downstream side. Numerical results have been validated with the experimental results. Also a thermal study has been conducted to study the effect of wall temperature on air flow mal distribution. Results reveal new features of flow mal-distribution which is helpful in better understanding of associated mal-distribution physics.

Keywords: Flow maldistribution, Multi -channel, U and Z- turn flow, Reynolds numbers.

1. INTRODUCTION

The problem of flow maldistribution and its impact on performance of process equipment has been realized by equipment designers and researchers in the past. One of the common assumptions in basic channel design theory is that fluid is distributed uniformly at the inlet of the channel. However in practice flow non-uniformity is observed which is known as maldistribution. In some cases its impact is so severe that it significantly alters the desired channel performance. A comprehensive review of flow maldistribution was first presented by Mueller at el. (1988). Most of the earlier works were concentrated on the effect of flow non-uniformity on the deterioration of the heat exchangers' performance with a parabolic inlet flow velocity profile. Fleming (1967) set up a flow maldistribution model in paired-channel heat exchangers and investigated the effect of flow maldistribution on the performance deterioration. London (1970) developed an analytical method in order to obtain the influence of passage-to-passage maldistribution on heat exchanger performance. Shah and London (1980) extended London's work and set up an n-size passages model. Chiou (1978, 1985) presented experimental data obtained from wind tunnel experiments and set up a continuous flow distribution model. He also investigated the thermal performance deterioration in cross-flow heat exchangers based on this continuous flow distribution model. Ranganayakulu et al. (1997) presented a numerical analysis using FEM where the effects of inlet flow non-uniformity on thermal performance and pressure drop in cross flow plate fin heat exchangers was investigated. They found that the performance deterioration and variation in pressure drop are quite significant. Ranganayakulu and Seetharamu (1999) studied the combined effects of wall longitudinal heat conduction, inlet flow non-uniformity, and temperature non-uniformity on compact tube-fin and plate fin heat exchangers.

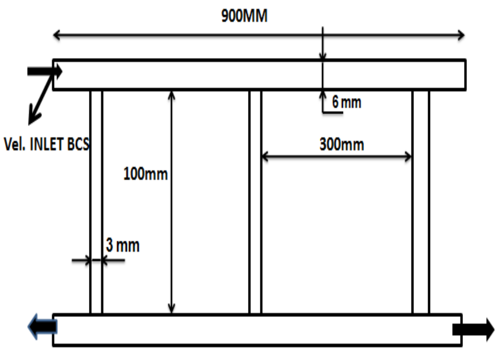
The summery of literature review shows the quantum and multi-dimensionality of work done on the subject of flow maldistribution. Most of the works are focussed on developing theoretical model or experimental work where one kind of problem has been targeted at a time. Few numerical works are present, but they also focus on similar aspect of the problem. Geometry induced maldistribution is known to be most significant and controllable from designer point of view. Such problem can be analysed numerically more effectively by using CFD techniques because local flow pattern is expected to rule non-uniformity in flow distribution. Present work is an effort to address this aspect of the problem numerically without jumping into geometrical complexities of case based problem analysis of flow maldistribution.

2. PROBLEM DEFINITION AND ITS MATHEMATICAL FORMULATION

To analyze the problem of flow maldistribution fundamentally and to bring out the microscopic facts, the flow is assumed to be distributed among several parallel channels of equal size creating U and Z- turn flow configuration as depicted in fig.1. These flow configurations are very common in plate type heat exchangers. For the U-type configuration bottom pipe right side is assumed to be closed and for Z-type bottom pipe left side is assumed to be closed. The objective of the problem is to study the affect of Reynolds number and wall temperature on maldistribution for both flow configurations.

To carryout numerical investigation the flow is assumed to be three dimensional steady incompressible viscous laminar where inertial and viscous forces are dominant. The effect of body force is assumed to be negligible. In the thermal analysis only

Convective and diffusive heat transfer has been accounted.



"Fig.1." U and Z- turn configurations

For steady incompressible Newtonian fluid flow,

Continuity Equation,

$$\nabla.\mathbf{V} = 0 \quad (1)$$

Momentum Equation,

$$\rho\frac{\partial \mathbf{V}}{\partial t} + \rho\mathbf{V}.\nabla\mathbf{V} = -\nabla p + \mu\nabla^2\mathbf{V} \quad (2)$$

Energy Equation,

$$\rho C_p\frac{\partial T}{\partial t} + \rho\mathbf{V}.\nabla\left(C_p T\right) = k\nabla^2 T \quad (3)$$

Where **V**, T, ρ and p represents velocity vector, temperature, density and pressure respectively.

The computation domain of the present problem consists of top and bottom headers of equal cross section connected with three flow channels of equal sized depicted in Fig.1. Following flow boundary conditions found to suitable and it has been implemented in present simulation work.

Inlet: Constant velocity inlet,

Outlets: Constant pressure,

Wall: No - slip.

The thermal study uses isothermal wall condition.

For easy and robust pre-processing of the computational domain ICEM has been used for meshing work. The simulation work has been carried out using FLUENT 6.3 solver. Some key features of present simulation work are,

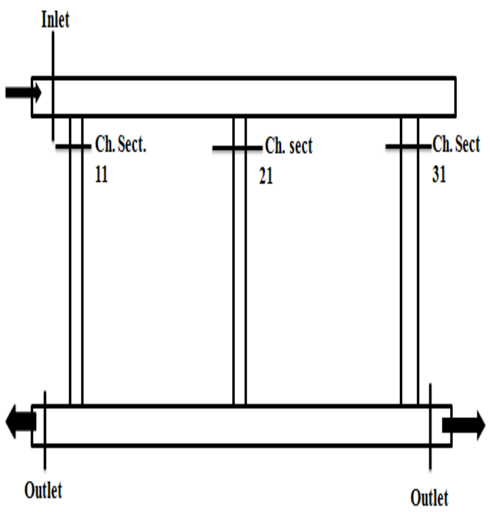
Solver algorithm: SIMPLE

Interpolation scheme: FOU

Turbulence model: κ-ω with turbulence intensity 2%

3. RESULTS AND DISCUSSIONS

This section deals with the results and its analysis of the problem under investigation. The geometrical parameters of the computational domain are illustrated in Fig. 1. This is a simple 3-D geometry. Analysis of the result has been presented based on flow configuration either U-turn or Z-turn. To represent the result precisely channels has been designated in specific manners which is shown in Fig. 2.



"Fig. 2." Designation of channel sections

Table.1. list the thermo-physical properties of water used in the simulation work.

Table.1. Property for water

Properties	Values
Density	998.20001 kg/m^3
Cp(Specific Heat)	4182 kg/m-s
Thermal Conductivity	0.6 W/m-k
Viscosity	0.001003 J/kg-k
Molecular Weight	18.0152kg/kg mol

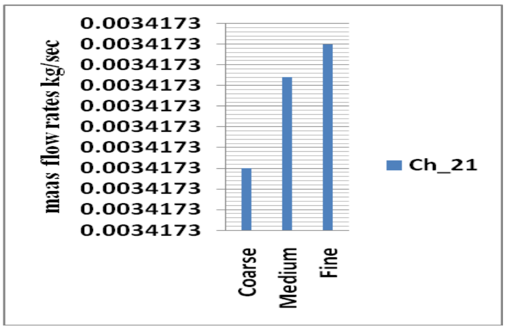
In present investigation Reynolds number has been varied from 1750 to 17600.

Grid Independence

In order to check the grid sensitivity of the results, various grid sizes has been tried before selecting an optimum grid size. Mass flow rate obtained at section 21 has been used to as a parameter to represent the grid independence. Results for three grid sizes have been presented here for illustration which is depicted in Fig. 3.

Mesh size considered are,

Coarse mesh: 325200 cells,
Medium mesh; 510336 cells
Fine mesh: 1364064 cells

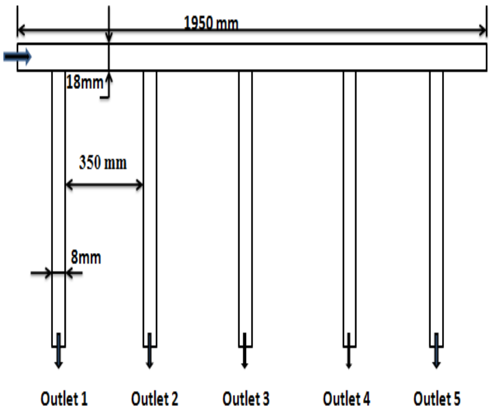


"Fig.3." Mass flow rates variations at channels section 21 for Re=1750

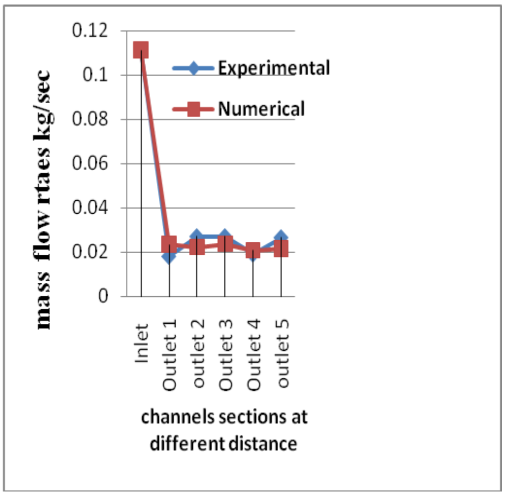
As it can be seen from the Fig.3, there is a little between deviation (less than 5%) in the result predicted for medium and fine mesh sizes. Therefore medium mesh size has been selected to carry out remaining simulation work.

Validation

As such there is no experimental or analytical work available in literature for the validation of the present work. So the present work has been validated by collecting experimental data on a simple setup specifically made for this purpose. Water has been used as medium for experimentation. The sketch of the setup is illustrated in Fig. 4.



"Fig. 4." Experimental set up for validation.



"Fig.5." Mass flow rates variations at Re=1950

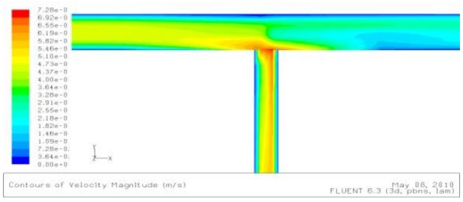
Figure 5 shows a close match between numerical and experimental work executed for validation purpose.

3.1. Effect of Re on maldistribution

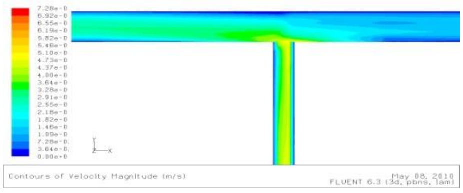
Effect of Re on flow maldistribution for U and Z turn flow configuration for water has been illustrated in following section with help of several plots and graphs. The results for U and Z turn flow configuration is expected to vary due to difference in energy potential (pressure head + kinetic head + datum head) available across each flow channel.

(a) U-turn flow configuration

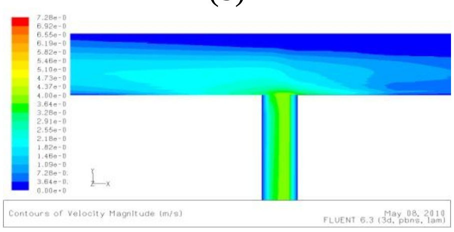
Figure 6 (a), (b) and (c) shows the velocity contours of water at section 11, 21 and 31 respectively at Re=1759. Figure 7 shows the velocity vectors of water at section 11, at Re=1759.



(a)

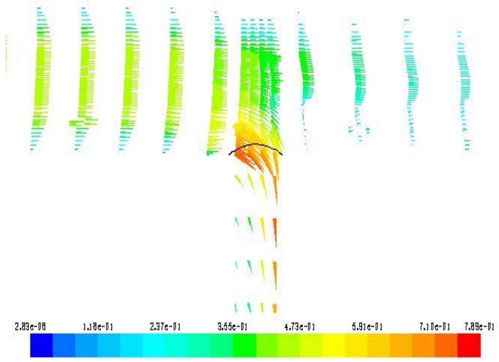


(b)



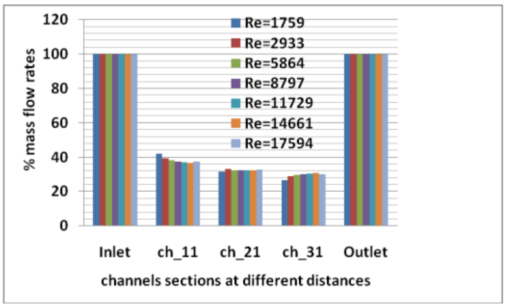
(c)

"Fig. 6." Velocity contours (Re=1759) at section (a) 11, (b) 12 and (c) 13



"Fig. 7." Velocity vectors (Re=1759) at section (a) 11

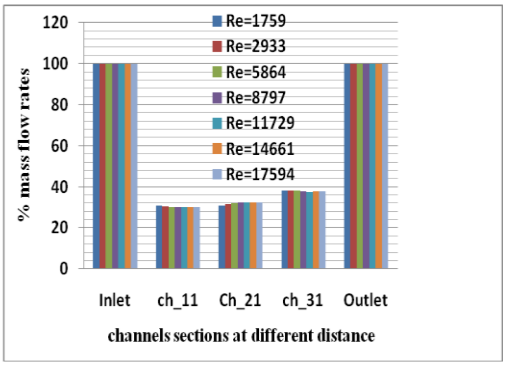
The difference in flow distribution at several channel section of equal size can be observed. The order of velocity magnitude is highest for the section 11 and goes on reducing along the downstream. Also a certain flow separation and recirculation at the first section can be observed which generally leads to flow obstruction and reduction in mass flow rate in the channel. At high Re this effect is expected to be more which leads to a significant change in flow distribution among channels. Existence of flow recirculation depends on local flow condition. Another important feature which can be observed is reducing magnitude of velocity which is because of lesser available mass flow rate at downstream side of the header which a natural reason for reducing flow in downstream channels.



"Fig.8." Effect of Re on percentage mass flow rate for U-turn configuration

It can be observed from Fig.8, the percentages mass flow rates at channel sections 11 decreases with the increase in Re. This feature can be attributed to increasing dominance of flow separation at higher Re where inertial forces become much stronger than viscous forces. A very mild increase in percentages mass flow rates with Re at channel sections 21 and 31 can be observed. This peculiar feature is probably due to reducing effect of flow reversal which is due to reduced local Re which the function of local velocity.

(b) Z-turn flow configuration:-

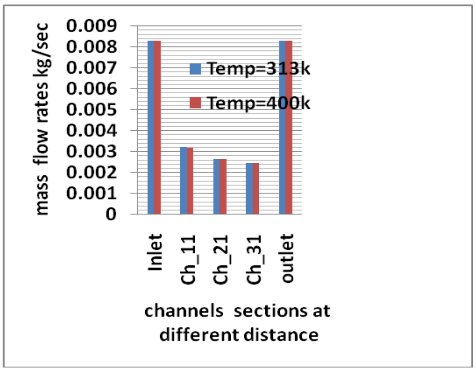


"Fig.9." Effect of Re on percentage mass flow rate for Z-turn configuration

In Z-turn flow configuration, first channel experiences highest energy potential difference and this difference goes on reducing in downstream side. Fig.9. shows the effect of Re on percentage mass flow rate at various sections. At a given Re, the percentage mass flow rate is found to be increasing in downstream side. This is reverse trend as obtained in U-turn flow configuration. This difference can be attributed to increased order of flow separation which goes on reducing in downstream due to weaker energy potential. Also it can be observed from Fig.6; percentages mass flow rates at all channel sections almost remain constant. This effect may be due to negligible impact increased Re compared to energy potential across a channel.

3.2 Effects of wall temperature on flow maldistribution:

This section deals with the effect of wall temperature on flow maldistribution which has been investigated for water and air for several Re.

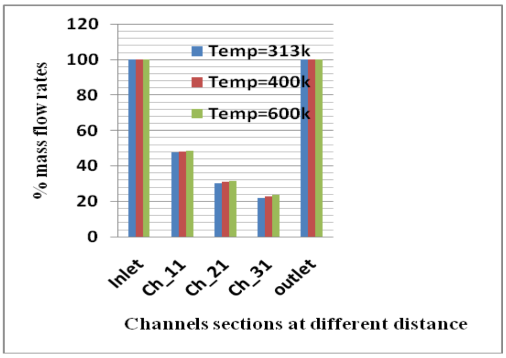


"Fig.10." Mass flow rates variation Re=1750, Temp=313k, 400k

It can be observed from Fig.10 that flow maldistribution is independent of temperature variations. This may be because of independence of density of working medium (water) with temperature in the range considered for investigation. But in the case of working medium air, variation of density with temperature is going to occur. So a maldistribution is expected under such cases. To verify this understanding the flow maldistribution problem was investigated with air where temperature variation is involved. Results obtained under various cases have been presented in following section.

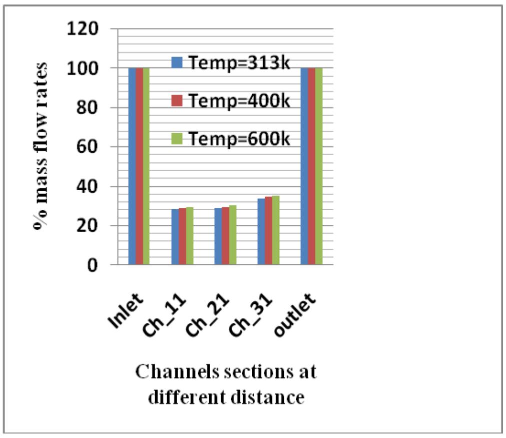
(a) U and Z-turn flow configuration

Figure 11 and 12 shows the effect of temperature on air flow distribution at different sections for U and Z-turn flow configuration at various Re. It is obvious from the figures that section 11 does not get influenced by temperature, but downstream channels experience some positive deviation with rising temperature. This feature can be attributed to bigger effect of temperature of air density variation.



"Fig.11" % Mass flow rates variation at Re=122 and temp=313k, 400k, 600k

So it can be concluded form this analysis that flow maldistribution due to temperature is independent of flow configurations.



"Fig.12" % Mass flow rates variation at Re=122 and temp=313k, 400k, 600k

4. CONCLUSIONS:

The following conclusions can be drawn from the present analysis.

- Flow maldistribution is an important parameter which needs to be accounted while designing a device where distribution a flow is involved.
- Flow maldistribution is a function of Reynolds number and thermal condition of wall.
- Effect of flow maldistribution is more severe in Z-turn flow configuration compared to U-turn flow configuration.
- In U-turn flow configuration, downstream channels receive lesser flow compared to upstream channels but Z-turn flow configuration show opposite trends.

6. NOMENCLATURE:

BCS	Boundary conditions
C_p, C_v	Heat capacity at constant Pressure, volume (J/kg)
Ch. sect	channel sections
κ	kinetic energy per unit mass (J/kg)
L	length(m)
m	Mass (kg)
$\dot{m}$	Mass flow rates (kg/s)
$\mathcal{P}$	Pressure (pa)
q	Heat flux (W/m^2)
R_e	Reynolds number
Temp	Temperature(K)
Vel.	Velocity (m/sec)

Greek symbols

α	Thermal diffusivity (m^2/s)
δ	Delta function (unit vary)
ϵ	Turbulent dissipation rates (m^2/s)
μ	Dynamic viscosity (Pa-s)
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
ω	Specific dissipation rate (S^{-1})

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