CFD Analysis To Study Single Phase Steam Distribution In A Vertical Tube Bundle

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Abstract - Fluid distribution in various geometries like plate heat exchangers, spargers, fuel cells, solar collectors etc. is very important for improved performance of these equipments. The header to tube ratio and the ratio of areas of the headers is extremely important and has been studied by researchers for a variety of equipments. We consider a slightly different geometry from the conventional ones in which the feed position is in the center of the header. A distributor plate is designed as an internal for the topmost header in an innovative manner depending on the header to diameter ratio. Three different configurations of with and without distributor design for steam distribution at different pressure have been chosen for this purpose. The best configuration has been selected and the non-uniformity is seen to reduce considerably with this configuration.

Keywords: IJSPR, International Journal, Research, Technology.

I. INTRODUCTION (10pt, Caps, normal)

Uniformity in flow distribution in any geometry (sparger, different manifolds: dividing, combining, parallel and reverse) needs proper balance between the pressure recovery and the frictional pressure drop [1]. Thus, for a given mass flow rate, the flow distribution depends upon header diameter, number and tube geometry (diameter of pipes, diameter of holes, pitch, etc.). During the past 50 years, although flow distribution in plate and frame exchangers, PEMFCs (Proton Exchange Membrane Fuel Cells) have received some attention, other applications of pipeline networks which are used in practice (air distribution in diffuser system of aerobic biological treatment, steam distribution in passive decay heat removal systems, etc.) have received comparatively less attention. The distribution of a fluid stream into a number of parallel substreams by means of the channels is accompanied by fluid pressure changes owing to the change of fluid momentum in the conduits, while the effect of wall friction in the conduits is negligibly small compared with that in the channels [2]. Such arrangements are found in industrial equipments (heat exchangers) where the flow is distributed from a main header to a number of tubes. Ample amount of research has been done on this problem by researchers over the past [1 – 14]. In such cases, the sudden changes in flow direction make the pressure rise in the top header and fall in the bottom header [16]. This pressure distribution leads to non-uniformity in the flow pattern and the flow in the channels will consequently increase in the direction of the inflow. Bassiouny and Martin, [2-3] derived expressions for predicting the velocity distribution, flow distribution, and pressure drop in such systems. The quantification of mal-distribution was done on the value of ‘m2’ (where ‘m’ is a parameter which depends on the diameter ratio and area ratio of the larger pipe (the header) and the individual tubes as in a pipe tube assembly) for all the three derivables. They concluded that for large positive or negative values of m2 the flow through some channels were practically absent giving rise to extensive mal-distribution. Lalot et al.[7] carried out extensive investigations on the change in flow distributions in electrical heaters, heat exchangers and condensers. They found that the efficiency of the equipment depended enormously on the flow distribution. Further, they concluded that the flow distribution improves with an increase in pressure drop. Lalot et al. [7] also recommended that placing a perforated plate as internal in the top header. They concluded that placing internal results in an increase in drag coefficient which decrease the maximum velocity by half. A detailed review of the work on flow distribution can be found in Gandhi et al. [16]. From the review of literature it was observed that all the work reported in the literature has been carried out with air or water as working fluid. In certain applications (Nuclear safety) vapors may also be used as working fluids. Gandhi et al. [16] have carried out extensive simulations and experimental work for different geometries where the inlet is from the middle rather than from the sides as in conventional headers. Gandhi et al. [16] considered different combinations of header diameter to tube diameter ratio’s variation of tube pitch and variation of number of tubes. Different configurations were considered to achieve reduction in non-uniformity. Gandhi et al.[16] concluded that the flow distribution can be improved without internals just by changing the header and tube diameters.

Gandhi et al.[16] have carried out simulations at high pressures and eliminated the middle tube for achievement of uniform flow distribution. However, in some situations where the geometry is such that the middle tube is exactly beneath the feed pipe then the use of internals may help in achieving better distribution. The present study has been carried out to see if by varying the pitch of the internal one can reduce mal-distribution. In the present study, a geometry similar to the one of Gandhi et al.[16] is considered (with flow from the center of the header and distribution in the tubes). The study is an attempt to see the effect of addition of internals to above mentioned geometry. Flow of steam at pressures (3atm < P < 20atm) and mass flow (0.3 < m < 1 kg/s) have been considered. CFD simulations have been performed for three different configurations: The original existing geometry and Type A (with distributor plate having modified pitch, 9 holes and middle hole at the center) and B (with with distributor plate having modified pitch, 9 holes and middle hole slightly off centered) with a distribution plate. The pressure distribution, velocity distribution and flow patterns have been presented. The type B configuration of the distributor has been seen to perform well and reduction in mal-distribution upto 90% has been obtained.

II. GEOMETRY

The geometry chosen for this system is a tube-header assembly consists of the top and the bottom headers which are assumed to have diameters D while the tubes have diameters dt. The ratio dt/D is assumed as 0.2. The inlet and outlet diameters are identical to the header diameters. Two configurations with different internals have been chosen. All the configurations with grids have been shown in Figure 1.

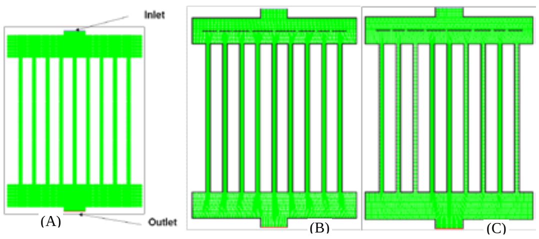

Figure 1 Mesh for all three distributors (A) Existing geometry (B) Configuration A with modified distributor plate (C) Configuration B with modified distributor plate

III. PROBLEM DEFINITION

A tube header assembly with top and bottom header having an inlet and outlet respectively and tubes vertically connected has been considered for the present investigation. The pitch between the tube centers is considered to be L=1.125H the header length being L. The height of the tubes is considered to be H, such that D = 0.1875H. The fluid enters at high pressures (3 < P < 20 atm) from the inlet and departs at the outlet. Due to a high diameter ratio between the tube header and the tubes the position of the inlet poses a problem. The problem mainly demands optimization of the pressure drop while keeping minimum maldistribution. The inlet being located at the center first it is decided to observe the flow distribution for the current geometry. It is then decided to use two different non-uniform distributors at the top header. The number of holes in the distributor equals (n-1) where n is the number of tubes. The diameter of each hole of the distributor is (dt/30) mm. The distributor has been arranged in such a way that the distance between each hole is different with the lowest distance being the one in the far end and the highest distance being one at the middle as can be seen in Figure 1. In the first configuration the central hole of the distributor corresponds to the opening of the center tube of the assembly while for the second configuration an off-center hole has been selected.

IV. GRID DETAILS

A two dimensional grid has been considered in the study. A non-uniform hexahedral mesh has been created for each configuration. For the geometry without the distributor the mesh size is 18,634 hexahedral cells with fine cells inside the tubes and walls and uniform mesh at the headers. The grid independency for the geometry without the distributor was carried out with three different grids namely 12,800, 18,600 and 23,200 and the centerline axial velocity was checked. Since the difference between the magnitude of centerline axial velocity was 1% for the 18600 and 23200 grids, 18600 grids was selected for investigation. Similarly, different grids were selected for the configurations selected for distributor and header tube assembly and best out of the three distributors was selected. For configuration 1 the grid cells were 36000 while for configuration 2 the number was 40,000.

V. GOVERNING EQUATIONS

The basic governing equations of continuity and momentum in Cartesian co-ordinates have been used. The k-ω turbulence model has been used for modeling the turbulence. The commercial software FLUENT 6.2.16 [15] has been used.

VI. METHOD OF SOLUTION

All the computational work has been carried out using the commercial software FLUENT 6.2.16. In case of k-ω model, QUICK discretization scheme was used for the turbulence parameters. For final sweep over each segment, upwinding has been performed using the QUICK with a second order pressure scheme. The QUICK formulation has a third order accuracy and which helps to mitigate the unfavorable effect of artificial diffusion that can occur when using low order upwinding schemes. All the discretized equations were solved in a segregated manner with the PISO (Pressure Implicit with Splitting of Operators) algorithm. In the present work, steady simulations were performed. All the solutions were considered to be fully converged when the sum of residuals was below 10-5. All the computations have been performed on an AMD64, cluster with a dual processor nodes with 2 GB RAM, 2.4 GHz processor speed.

VII. RESULTS AND DISCUSSION

In this section, we first present the pressure and velocity distribution both qualitatively and quantitatively. By incorporating proper internals the distributions are revisited.

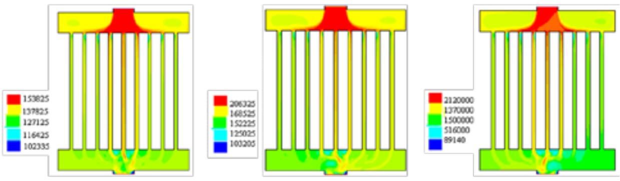

Figure 2: Pressure contours for three different pressures (a) 1.5 atm (b) 2 atm (c) 20 atm

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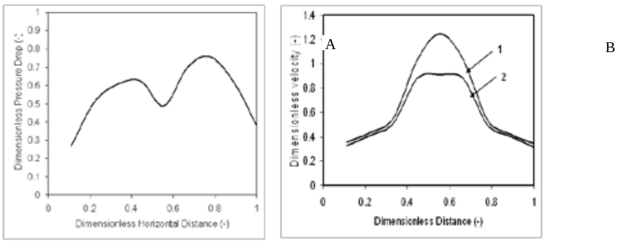

Figure 3: (A) Effect of dimensionless pressure drop with dimensionless horizontal distance (B) Effect of non-dimensional velocity on non-dimensional horizontal distance (1) At the inlet of the central tube (2) At the outlet of central tube

The pressure drop is calculated by taking the difference in pressures for each tube at the centerline of the top and bottom headers. The pressure drop profile is shown quantitatively in Figure 3A. At the top and the bottom headers, high velocities at the inlet are observed, which means that all the fluid passes from the center of the tubes as shown in Figure 3B. The parameter developed analytically by Bassiouny and Martin [2-3] ('m2') shows important observation. The fraction of mean velocity going into the tubes and ratio of the areas of the top and bottom headers are the most important in determining the distribution. The parameter takes negative and positive values depending on the above two factors. For values greater than 1, the pressure drop in the channels increases as per the analysis of Bassiouny and Martin [2-3]. The velocity distribution also reaches uniformity when the values of 'm2' nears 1. In the present work, we design a distributor in such a way that the area ratio of header to tube are kept constant and the fraction of mean velocity going to the tubes are varied by placing a distributor as an internal.

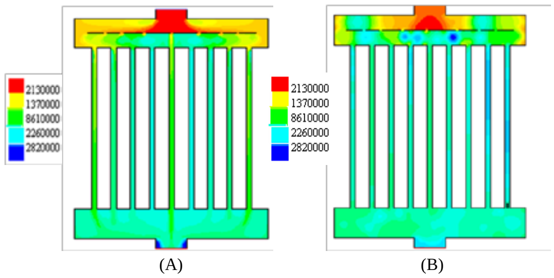

Figure 4 Pressure contours of two different kinds of non-uniform distributor (A) Center hole (B) Off center hole

The best two configurations have been reported in the present work with 'm2' values of 0.97 and 1.1 respectively.

$$m^2 = \frac{2-\beta^*}{2-\beta}\left(\frac{A}{A^*}\right)^2 \qquad (1)$$

where, is the average velocity ratio at the inlet and is the average velocity ratio at the outlet, A is the cross sectional area at the inlet while A* is the cross-sectional area at the outlet and Ac is the cross sectional area of the tubes. The two internal distributors have been designed as follows: The ratio of hole diameter in the distributor to the tube diameter is kept equal to 0.25. The pitch between the holes is varied non-uniformally such that the hole lies between the spacing between two consecutive tubes of the distributor. Using this combination we have tried to vary the fraction of the mean velocity going into the tubes. Figure 4 shows the pressure distribution for the two designs considered. In design A, the 5th hole of the distributor is at the center, while for design B the same tube is slightly offset from the center. As seen in Figure 4A the pressures are higher at the end tubes for configuration A. If we number the holes from 1 to 9 from left to right then the pressures are around 8 atm on tube 1, 5 and 9 where as all other tubes have pressures less than 2 atm. Figure 5A shows that the velocities are lowest at the tubes 3 and 6 respectively while at the 5^{th} tube the velocity is highest. The extent of non-uniformity is defined similar to [16] as is given as

$$\text{ENU } (E_i) = \frac{m_i - m_{avg}}{m_{avg}} \qquad (2)$$

Where m_i is the mass flow rate of individual tubes while m_{avg} is the average mass flowrate. The ENU for configuration A is 50% while with B reduces to 20%.

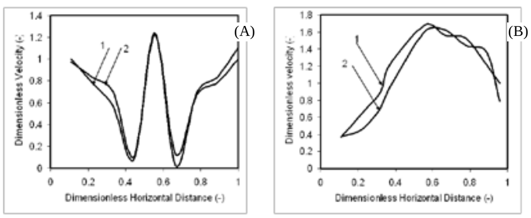

Figure 5 (A) Effect of non dimensional velocity on non dimensional horizontal distance at the inlet of the central tube (1) Design A (2) Design B (B) Effect of non dimensional velocity on non dimensional horizontal distance at the outlet of the central tube (1) Design A (2) Design B

VIII. CONCLUSIONS

CFD simulations have been carried out for header tube geometry where inlet and outlet are at the middle of the top and bottom headers. It is seen that at low pressures the extent of non uniformity increases with an increase in pressure when no distributor plate is provided. A distributor plate used as an internal at the top header also needs a specific variation of length between the holes. The pitch between the holes has a relationship. With the best designed configuration an optimized solution between the extent of non-uniformity and pressure drop is obtained. With the newly designed distributor the extent of non uniformity is reduced to 20%

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