NUMERICAL COMPARISON OF THE TUBE BANK PRESSURE DROP USING A CONVENTIONAL NOZZLE POSITION AND AN INLINE NOZZLE POSITION OF A SHELL AND TUBE HEAT EXCHANGER

Kartik Ajugia[1], Kunal Bhavsar[2]

[1] Student, Mechanical, SPCE, Maharashtra, India

[2] Workshop Superintendant, Mechanical, SPCE, Maharashtra, India

E-mail- kartik_ajugia@yahoo.com ,kunal002@gmail.com

Abstract— The main parameters describing the efficiency and acceptance of a particular shell and tube heat exchanger in any application is its pressure drop. More the pressure drop across the tube side less is the heat transfer and hence more is the pumping power required and more is the cost. The pressure drop on the tube side can be split into three parts namely pressure drop due to Inlet nozzle, pressure drop in the tube bank, and pressure drop in the outlet nozzle. A large number of analytical expressions are available for finding the tube bank pressure drop of a Conventional SHTX i.e. as per TEMA Standards. This research provides a Numerical approach for finding the pressure drop across the tube bank for a SHTX with a nozzle position other than the TEMA Standards and also its comparison of the tube bank pressure drop with a conventional BEM types of TEMA SHTX. Firstly the Conventional Nozzle position is used for an Elliptical Inlet and Outlet headers i.e. the nozzle length being perpendicular to the direction of flow in the inlet and outlet header and secondly the nozzle length being parallel to the direction of flow in the inlet and outlet header. Since the approach is numerical the use of Ansys 14.5 was used. ICEM was used for the geometry making and meshing. The meshed file was then exported to the Fluent for the solving process. After doing the solver setup and using appropriate boundary conditions the solution was found keeping in mind that the flow was steady and isothermal. The pressure zones computed at the Inlet header were compared between the two cases. Also the pressure drop across the tube bank were calculated for each case and compared. The results obtained from the Conventional Nozzle position were validated against the theoretical pressure drop and the same model and approach was used to find the Tube Bank pressure drop for an Inline Nozzle.

Keywords — Numerical, Comparison, Tube Bank Pressure Drop, Nozzle Position.

INTRODUCTION

A heat exchanger is a device used to transfer heat from one medium to another by separating them to prevent mixing or allowing them to mix and transfer the heat. One such exchanger which prevents the mixing of the mediums is a shell and tube heat exchanger. There are various types of shell and tube heat exchangers based on their geometrical specifications. However for the present analysis a TEMA BEM [1] and its modified type of SHTX has been used. The pressure drop plays an important role in the overall efficiency of a SHTX. The total tube-side pressure drop ΔPT for a single pass comprises the pressure drop in the straight tubes (ΔPTT), pressure drop in the tube entrances, exits and reversals (ΔPTE), and pressure drop in nozzles (ΔPTN) [2]. The uniform distribution of flow in tube bundle of shell and tube heat exchangers is an assumption in conventional heat exchanger design as claimed by Bejan and Kraus [3]. Traub [4] found that increased turbulence levels lead to an improvement in the heat transfer for tube banks and at the same time increasing the pressure drop. Achenbach [5] found that rough surfaces on the tubes of in-line arrangements in cross-flow have the potential to decrease the pressure drop while simultaneously improving heat transfer.

PHYSICAL MODELLING

Physical modeling involves the creation of the actual 3-D model of a SHTX. A large number of manufacturing firms were visited inorder to obtain the 2-D drawing of a SHTX. CANAAN Engineering works located at Kandivali, Mumbai, India was generous enough to provide a 2-D AutoCAD drawing of an actual SHTX to be manufactured and used at an industry in Hazira, Surat. The fluid to be circulated was chosen as water. The geometrical specifications and the fluid properties are as shown in table no – 1.

Table -1: Geometrical Specifications and Fluid Properties

Sr No	Geometrical Parts	Specifications
1	Inlet/Outlet Header	Elliptical Ends 2: 1
2	Shell or Header I.D	304.8 mm

3	No of Tubes	77
4	Tube O.D	19.05 mm
5	Tube Thickness	1.65 mm
6	Inlet and Outlet Nozzle I.D	66.64 mm
7	Nozzle Lengths	212 mm
8	Tube Pitch	25.4 mm
9	Tube Layout	Triangular (60^0)
10	Tube Length	1518 mm
11	Overall Length	2492.94 mm
12	Fluid circulated	Water
13	Fluid Density	998.2 kg/m^3
14	Fluid Viscosity	0.001003 kgm/s^2

Based on the above geometrical specifications and the 2-D drawing ICEM was used to create the 3-D drawing of the SHTX to be used for the analysis. The thickness of the surface was not taken into consideration as the analysis was restricted to the pressure analysis. Figure number 1 shows the tube bank geometry. Figure number 2 and 3 indicate the overall geometry of the SHTX with conventional nozzle position and the modified nozzle position respectively.

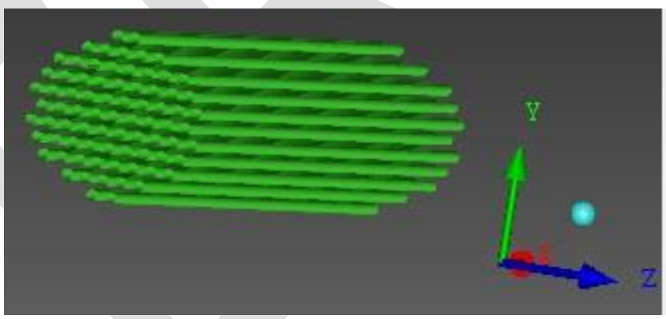

Fig -1: Tube Bank Geometry

The tube bank and the Inlet and Outlet header geometry remain same for both the conventional and inline nozzle position.

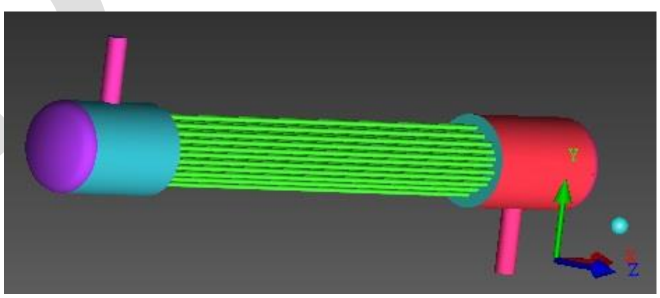

Fig -2: Full Geometry with Conventional Nozzle Position

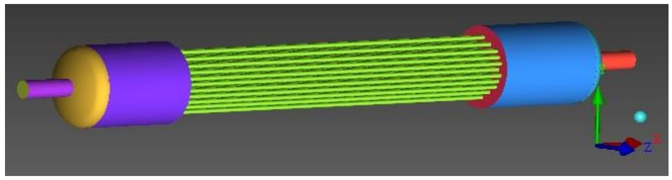

Fig -3: Full Geometry with Inline Nozzle Position

MESHING

Both geometries as shown in figure number 2 and 3 were meshed using ANSYS ICEM 14.5. Firstly the surface mesh was created by doing the global, surface and the curve mesh setup. The method specified in the setup was tetra mixed robust octree.

The surface mesh was further processed for prism mesh. Two layers were specified for prism mesh near curved surfaces inorder to capture the effects accurately for flow near boundaries. Fig 4 and 5 indicates the mesh of the two nozzle positions.

Fig -4: Mesh of Conventional Nozzle Position

Fig -5: Mesh of Inline Nozzle Position

The mesh was obtained with a very good quality with the minimum value of 0.25 in both the cases. However there were a very few nodes which had a slightly lesser quality than that indicted which was neglected as they were very small in number. The meshed file was then imported in ANSYS FLUENT for analysis.

SOLVER SETUP

The solver used for obtaining the numerical solution was ANSYS FLUENT. The governing equations used by the solver shall include the Continuity and the Navier Stokes Equation i.e. the Momentum Equations in three dimensions.

The boundary conditions used for the solver setup are as shown in table no – 2.

Table -2: Boundary Conditions

Sr No	Name of the Zone	Boundary Condition	Boundary Characteristics
1	Inlets	Velocity Inlet	3.31 (m/s)
2	Outlets	Pressure Outlets	0 Gauge Pressure
3	Inlet Wall		

4	Outlet Wall	Wall	No Slip, Surface Roughness 0.5, Stationary
5	Tubewalls		
6	Header Walls		

The solution method used was the "SIMPLE" Algorithm and the spatial discretization was based on Second Order Upwind Scheme. The turbulence model used was the standard k-ε model. The solution residuals were iterated for a precision upto 0.0001.

RESULTS AND ANALYSIS

a) Analytical Pressure Drop across the Tube Bank

The input velocity to the nozzle was chosen as 3.31 m/s. The tube side pressure drop comprises of the pressure drop due to friction losses inside the tubes (1) plus the pressure losses due to sudden expansion and contractions (2) which is accounted by four velocity heads per pass [6]. Therefore the total pressure drop for the tube side fluid flow is given by (3)

$$\Delta P_t = 4 * f * L * N_p * \rho * U^2_m \;/\; (2 * d_i) \qquad (1)$$

$$\Delta P_r = 4 * Np * \rho * U^2_m / 2 \qquad (2)$$

$$\Delta P_{total} = (4 * f * L * N_p / d_i + 4 * N_p)\, \rho * U^2_m / 2 \qquad (3)$$

Where

ΔP_t and ΔP_r are the pressure losses due to friction and sudden expansions and contraction respectively

L – Length of the tubes (1.518 m)

N_p - No of passes (One Pass)

d_i - Inner diameter of the tubes (0.01575 m)

U_m – Mean velocity of Fluid in the tubes

f – Friction factor, ρ – Density of the fluid (998.2 kg/m^3)

The friction factor f is given by Moody's chart for turbulent flow through uniform circular pipes [7] i.e. $f = 0.079Re^{-0.25}$ where Re is the Reynold no for the fluid.

As per the given conditions the pressure drop for a single pass tube side was found to be analytically = 2038 Pascal.

Another correlation for the tube side pressure drop was given by R. W Serth[2] who suggests that the total tube-side pressure drop ΔPT (4) for a single pass comprises the pressure drop in the straight tubes (ΔPTT) (5), pressure drop in the tube entrances, exits and reversals (ΔPTE) (6).

$$\Delta PT = (\Delta PTT) + (\Delta PTE) \qquad (4)$$

Where

$$\Delta PTT = K_{PT1} * N_P * L * u_T^{(2 + m_f)} \qquad (5)$$

$$K_{PT1} = 2 * F_C ((\rho * d_1 / \mu) \wedge m_f) * \rho / d_1$$

$$F_C = 0.0791,\ m_f = -0.25 \text{ for } Re \geq 3000$$

$$\Delta PTE = K_{PT2} * u^2_T \qquad (6)$$

$K_{PT2} = 4 * \alpha_R * \rho$

$\alpha_R = 2\ N_p – 1.5$

u_T - mean velocity of the fluid through the tubes which is the same as that obtained above

It was observed that using the above correlation also the pressure drop was found to be 2038 Pascal.

b) Numerical Pressure Drop across the Tube Bank

The meshed files were imported and after doing so the Solver setup mentioned earlier, they were iterated for 1000 iterations. The solutions converged in less than 300 iteration. The origin for the geometries was at the tip of the Elliptical wall at the inlet header. The distance between the origin and the start of the tube bundle is 392 mm. Inorder to find the numerical pressure drop a number of Z-Coordinates i.e. vertical sections in the X – Y plane passing through the vertical tube arrays i.e. and passing through the center of the tubes were created. The central Z-Coordinate was named as Z-0.

Moving along the positive Z axis along the tube bank array in X-Y plane each vertical tube array is separated from each other by half the pitch i.e. 25.4/2 = 12.7 mm. At each and every such vertical tube array in X-Y plane a Z-Coordinate was created.

Therefore a total of 19 such Z- Coordinates were created for both the converged files inorder to capture the 77 tubes of which 9 were along the positive Z – axis and 9 along the negative plus the center one which can be visualized from the tube bank array shown in fig 1.

Also an X coordinate at a distance of 5 mm away from the tube start was created. Thus a combination of the various Z Coordinates and the single X Coordinate the pressure at the inlet of each and every tube was found out for both the geometries. A gap of 4 mm was left between the tube start and the X Coordinate inorder to capture the pressure changes due to entrance effect of fluid inside the tube from the header.

The fig 6 and fig 7 shows the Z – 0 coordinate of contours of total pressure variation for both the nozzle position. The X-Coordinates for the two cases are shown by fig 8 and 9. However a combination of both Z and X Coordinate used to find the tube inlet pressure for inline nozzle arrangement is shown in figure 10.

Fig -6: Z-0 Coordinate of Conventional Nozzle Position

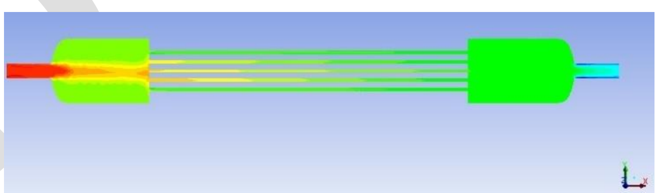

Fig-7: Z-0Coordinate of Inline Nozzle Position

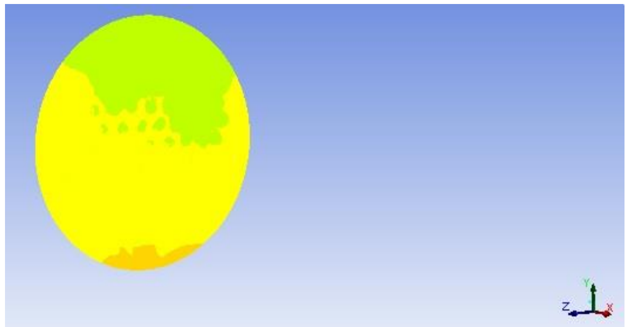

Fig – 8: X-Coordinate for Conventional Nozzle Position

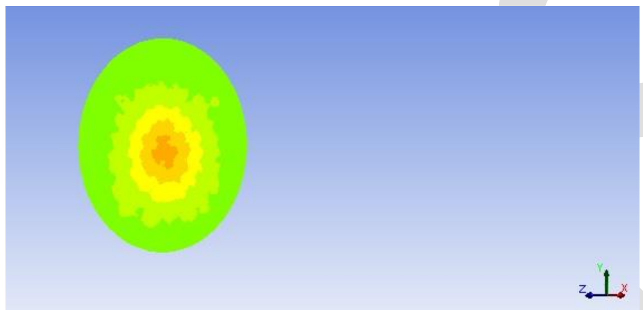

Fig -9: X-Coordinate for Inline Nozzle Position

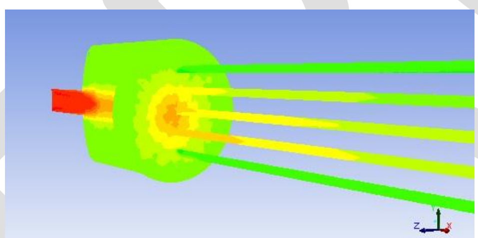

Fig -10: Z-X Coordinates for Inline Nozzle Position

c) Grid Independence Test

Before running the simulation an optimized mesh needs to be found out in terms of the accuracy of the results and the lesser number of nodes inorder to reduce the computation cost.

The conventional geometrical model was meshed for three different dimension inorder to obtain a coarse, medium and a fine mesh. The numbers of cells thus obtained are mentioned in the table no – 3.

Table -3: Name of the Table

Sr No	Mesh Type	No of Cells	Average Pressure Drop
1	Coarse Mesh	1986668	1918
2	Medium mesh	2519375	1943
3	Fine Mesh	3709885	1912

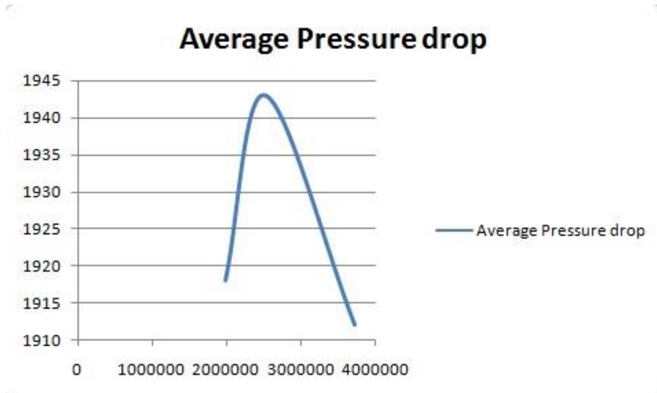

Fig -11: Grid Independence Test for Conventional Nozzle Position

The fig no - 11 indicates that the average pressure drop first increases reaches optimum and then starts decreasing as the fineness goes on increasing. Thus the optimum mesh used for further simulations was the medium mesh for the conventional and the same mesh size parameters were used for the inline nozzle position. The mesh gave a maximum accuracy with a -4.6 % deviation from the theoretical results for the conventional nozzle position. The medium mesh chosen also helps to reduce the computation cost compared to that of the fine mesh. However for the inline nozzle position there were 2540756 cells or 492881 nodes with the medium mesh.

d) Inferences

For the Conventional Nozzle Position:

- A two set of pressure values were obtained at the inlet of the tubes.
- The tubes with green color at the start of the tubes in the fig no 6 indicates a pressure value of 10506 Pa while the yellow color indicates 11285 Pa.
- All the 77 tubes were observed at the inlet side with the help of Z and X Coordinates to get the inlet pressures of the respective tubes.
- 38 tubes were having a pressure inlet of 11285 Pa while 39 tubes were having a pressure inlet of 10506 Pa.
- It can be observed from fig no 6 as that at the outlet all the tubes had a uniform pressure i.e. there is not much variation.
- The outlet pressure was observed as 8947Pa.
- Therefore the average pressure drop can be calculated as [(39 * 10506 + 38 * 11285) – 77* 8947] / 77.
- From the above calculation the average pressure drop was found to be 1943.5 Pa while the theoretical average pressure drop is 2038 Pa.
- The difference between the theoretical and the numerical analysis is less than 10% which is within the acceptable range, hence the results are validated.

For the Inline Nozzle Position:

- A five set of pressure values were observed across the 77 tubes as seen from fig no 9 in the form of rings.
- The pressure values obtained are 13536 Pa (1 Tube) at the centermost region indicated by brown color, the region surrounding it i.e. the light brown has a value 12823 Pa (9 Tubes). Then we have 12111 Pa (12 Tubes) indicated by yellow color. The yellowish green region has a value of 11399 Pa (33 Tubes) and the outermost light green color has a value of 10687 Pa (22 Tubes).
- It can be observed from fig no 6 as that at the outlet all the tubes had a uniform pressure i.e. there is not much variation.

- The outlet pressure was observed as 9262 Pa.

- Therefore the average pressure drop can be calculated as [(1*13536 + 9*12823 + 12*12111 + 33*11399 + 22*10687) – 77*9262] / 77.

- From the above calculation the average pressure drop was found to be 2238 Pa while the theoretical average pressure drop is 2038 Pa for the conventional position.

- Therefore a difference of +10.2 % was observed between the two.

e) Parametric Study

The simulations were run for different input velocities of 2m/s, 5m/s and 7 m/s at the inlet nozzle and a relationship between the theoretical and numerical pressure drops were observed. Table no – 4 indicate the parametric study.

Table -4: Parametric Study

Input Velocities	2 m/s	3.31m/s	5m/s	7m/s
ΔP_{theor} (Pa)	787.4	2038	4467	8468
ΔP_{num} (Conventional)	720	1943	4431	8421
ΔP_{num} (Inline)	818	2238	4981	9263
% Deviation Conventional	-8.5	-4.3	0.0	0.0
% Deviation Inline	4.05	10.2	12.42	10

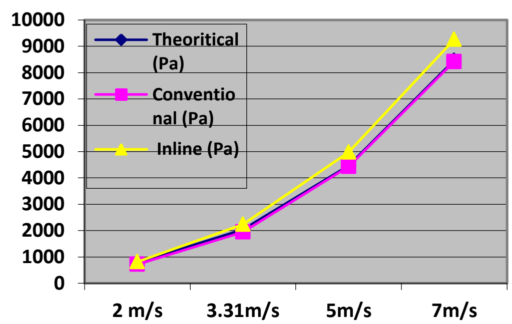

Chart -1: Parametric Study

- Chart 1 is a graph indicating the parametric study of pressure drop against different velocities for the theoretical, Conventional and Inline position.

- The dark blue colored curve is the theoretical, pink is for the Conventional Nozzle pressure drop whereas the yellow colored is for the Inline Nozzle pressure drop.

- The theoretical and the Conventional Nozzle Position pressure drop are well in conversant with each other whereas the Inline Nozzle pressure drop is higher than them for all the situations.

- The maximum deviation of Inline Nozzle position was at 5 m/s with percentage deviation of +12.42 %.

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CONCLUSION

- Two set of pressure values were obtained 10506 Pa and 11285 Pa were observed on the inlet side of the tube bank for the Conventional Nozzle position whereas five set of pressure values (13536, 12823, 12111, 10687, 11399) Pa were observed at an inlet velocity of 3.31 m/s.
- The % deviation of the pressure drop was on the negative side for the Conventional Nozzle position whereas it was on the positive side for the Inline Nozzle as shown in table no -4.

Since the pressure drop is more for the Inline Nozzle it is better to use a Conventional Nozzle position, which in turn reduces the pumping cost for the fluid on the tube side.

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