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DOUBLE PERFORATED IMPINGEMENT PLATE (DPIP) IN SHELL-AND-TUBE HEAT EXCHANGER

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ABSTRACT

This paper presents a solution to a chronic problem causing repeated tube failure at shell-and-tube heat exchangers. The problem is related to fouling process on tubes surface which accumulates downstream the impingement plate at exchanger inlet nozzle within the first tube rows due to low velocity and vortices production. In fouling services, the suspended deposits, fouling, accumulates on tubes surface downstream the impingement plate causing under-deposit corrosion and raising tubes surface temperature due to lack of cooling accelerating fouling process. Under fouling corrosion attacks tubes and causes repeated tube failure costing a lot of money in terms of material, maintenance and production losses.

Normal practice of extending tubes life and delaying their failure is to upgrade the tubes metallurgy. So this paper objective is to present an economical solution option through modifying the impingement plate in shell-and-tube heat exchangers where impingement plate is recommended by Tubular Exchanger Manufacturers Association, TEMA. The impingement modification is to replace the solid conventional impingement plate with double spaced plates having offset holes, called Double Perforated Impingement Plate (DPIP).

The objective of this work can be met through simulate and compare shell side inlet flow distribution around the conventional and modified impingement plate, DPIP, and insuring of enhancing the flow pattern distribution at the area behind impingement plate. Since experimental work in flow investigation can be time consuming and costly, computational fluid dynamics, CFD, fluent software was implemented as a cost effective helpful tool to conduct the simulation and comparison purpose.

The modified impingement plate, DPIP, will destroy vortices created behind the conventional plate retarding fouling accumulation principal. DPIP will enhance shell side flow distribution downstream the impingement plate and stop fouling accumulation on the tubes to prevent under-deposit corrosion.

INTRODUCTION

Fouling is defined as the accumulation of undesirable deposits on a heat transfer surface (Shah and Sekulic, 2003). Fouling in shell-and-tube heat exchangers is expected in both shell and tube sides due to their special design having many areas with stagnant or semi-stagnant portions where velocities are very low or negligible. Since fouling can affect the heat exchanger performance as well as equipment integrity at stagnant locations, it is required to eliminate stagnant locations by allowing flow through them (Saunders, 1988). The impingement plate which is used mainly to protect tubes against shell side inlet flow impingement, it eliminates some stagnant locations and creates others.

The impingement plate is placed inside the shell facing the shell inlet nozzle and usually attached directly to the bundle by tack welding to the tie-rods. It is used mainly to protect tubes portion facing shell inlet nozzle against potential erosion corrosion phenomenon and vibration impact of high-velocity. It is recommended by TEMA to use impingement plate when ρV^2 value exceeds a certain value as shown in Table 1 (Saunders, 1988):

Table 1. TEMA Criteria for Impingement Plate

Type of fluid	ρV^2 (kg/m.s^2)	ρV^2 (lb/ft^2)
Non-corrosive, non-abrasive single phase	2230	1500
All other liquids, including liquid at its boiling point	744	500
All other gases, vapors, saturated vapors and liquid mixtures	All Value	All value

The main function of impingement plate is as follows [5]:

1. Eliminate erosion corrosion of tubes facing the inlet shell nozzle
2. Eliminate flow induced tube vibration source at shell inlet nozzle

3. Careful design of the impingement plates can go far in stimulation fluid motion in the stagnation areas near the ends of the tubes to tubesheet to:
   a. Utilize the area effectively for heat transfer
   b. Avoid surface temperature increase which prolong the life of the tubes

With all previous advantages, installing impingement plates may cause some problems. One of well experienced problem happens with contaminated services when a stagnant area is created behind the impingement plate. The consequences of having stagnant areas are often very serious and can be summarized as follows (Walker, 1982):

1. The obvious effect is that with low fluid velocity, the area for heat transfer is not effectively utilized
2. Corrosion and fouling processes are highly accelerated under stagnant conditions
3. Contaminated streams aggregate preferentially in the low-velocity areas.
4. Surface temperatures in the low-velocity areas may appreciably exceed the mean design condition, which further accelerates fouling processes.

Our experience with tubes failure due to fouling accumulation/processing on the tubes surface behind impingement plates in different TEMA-types of tabular heat exchangers leads to try different modifications of impingement plate. An example of tubes failure behind the impingement plate is shown in Figure 1 due to under-deposit corrosion attacks tubes located behind the impingement plate where fouling materials find a suitable place to deposit on tubes and attacks the surface.

One example of impingement modification was at kerosene stripper exchanger, BHS-type, suffering from severe fouling and tubes external corrosion located behind impingement plate and causing tube failure. The tubes failure caused plant shutdown for re-tubing activities several times during the life of the exchanger. Since the tubes pattern is square, plant engineers succeeded and resolved the problem by opining narrow slots in the conventional impingement plate facing the spaces between tubes. To prevent shell-and-tube heat exchangers with different tube pattern, such as triangular or rotated square tube, etc. from such tubes attack, this paper presents a different modification, called Double Perforated Impingement Plate (DPIP).

Much work in the field of fluid and CFD simulation was conducted. At HTRI (Kevin, 2003), engineers recently performed a series of CFD simulations using k-ε model to compare the performance of each of the main impingement device types solid plates, single perforated plates, and rod grids and evaluated the sensitivity of each type. The general conclusion was to use impingement rods even though it is much costly.

The objective of this work is to resolve fouling accumulation behind impingement plate by eliminating the root cause of flow vortices created behind impingement plate by using a new modification of tubes protection.


Fig. 1-a) Fouling Accumulation on the Tubes


Fig. 1-b) External Tube Corrosion

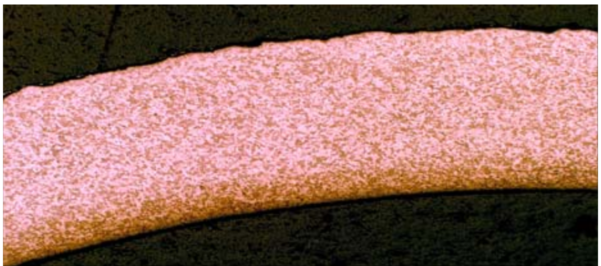
Fig.1-c) Inner and Outer Tube Surface, X20

Fig. 1 Example of Real External Tube Corrosion

CONVENTIONAL IMPINGEMENT PLATE DESIGN

The heat exchanger shown in Figure 2 shows a 1-2-shell-and-tube heat exchanger, TEMA AET-type. It shows the shell inlet fluid entering the shell at the top. There exist two impingement plates where the upper one is facing the shell inlet nozzle and the lower one is in the opposite side of the bundle facing the shell inlet nozzle in case of rotating the bundle at special operation cases. So the conventional impingement plate (Saunders, 1988), is a small flat or curved plate placed inside the shell facing the shell inlet nozzle. The normal distance between the nozzle opening at shell side and the upper surface of the impingement plate is 25% of the shell inlet nozzle diameter, 1/4D. It is usually fabricated in square shape with sides' length two inches more than the nozzle diameter. Its thickness usually is about 6 mm. It is attached directly to the bundle by tack welding to the tie-rods.

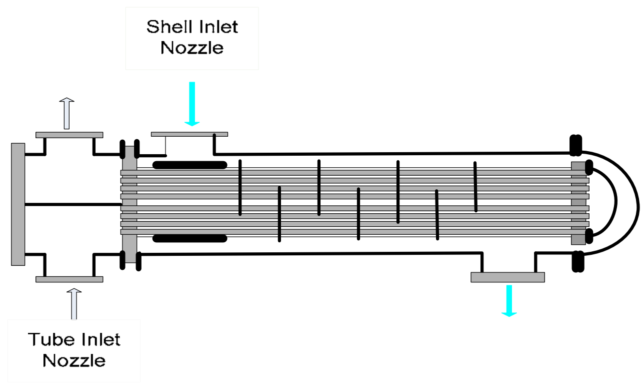

Fig. 2 1-2-shell-and-tube heat exchanger, TEMA AET-type

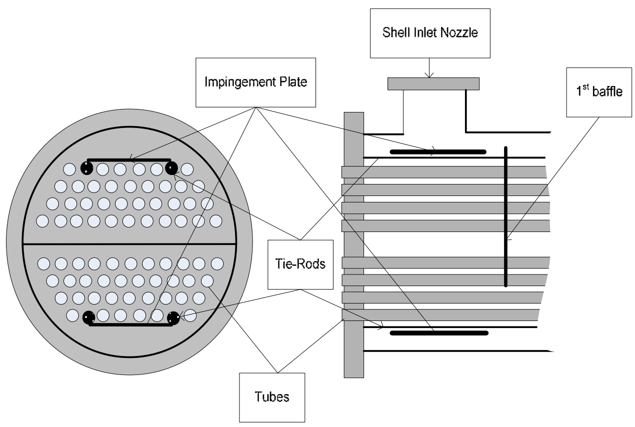

Fig. 3-a Conventional Impingement Plate Location

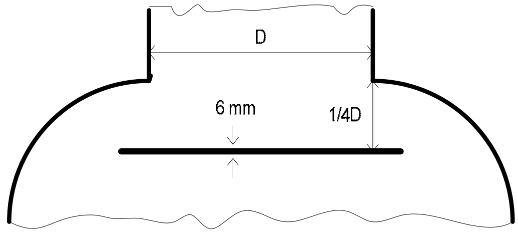

Fig. 3-b Conventional Impingement Plate Dimension

MODIFIED IMPINGEMENT PLATE, DPIP

The modified impingement plate is composed of two spaced perforated plates with offset holes. Both plates have the same size with same dimensions as the conventional impingement plate. The modified impingement plate is called Double Perforated Impingement Plate, (DPIP), and is used to replace the solid conventional impingement plate as shown in figure-4.

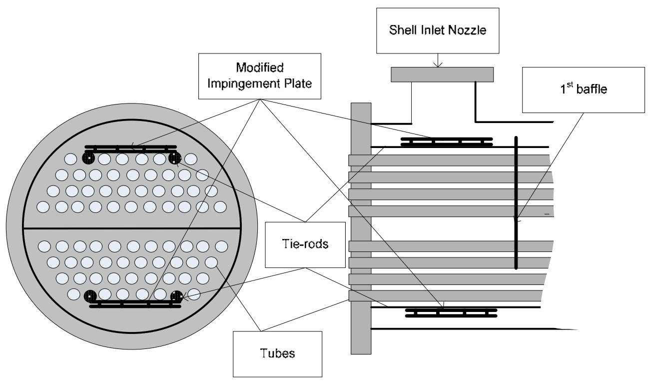

Fig. 4-a Modified Impingement Plate, DPIP, location

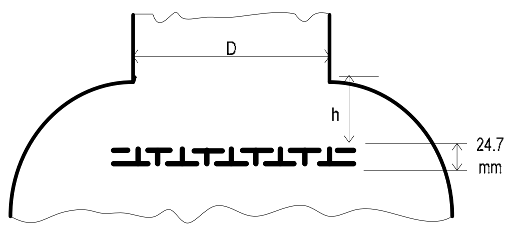

Fig.-4-b Modified Impingement Plate 25.4 -25.4 mm (1.0 -1.0"), DPIP,

DPIP is selected to be with the following parts to prevent shell-and-tube heat exchangers of different tube pattern, such as triangular or rotated square tube, etc. from tubes external fouling accumulation attack. DPIP consists of:

1. Upper plate: a square plate with 25.4 mm circular holes, blue colour, distributed over the surface as shown in Figure 5-a. It has sides' length of 50.8 mm more than the shell inlet diameter and 6mm thickness.
2. Pins: used to hold the two plates 12.7 mm apart and distributed evenly and tack welded into both plates as shown in Figure 5-b.
3. Lower plate: a square plate with 25.4 mm circular holes, red colour, as shown in Figure 5-c. It has a sides' length of 50.8 mm more than the shell inlet diameter and 6 mm thickness.

The DPIP parts combination is presented in Figure-6. Figure-6 shows different views of DPIP design with 25.4 mm holes of the upper and lower plate and 12.7 mm side gap. The figure shows expected flow distribution leaving the plates from all sides. Holes in the upper plate allow part of the shell side stream flow to pass into the combined plates and distributes between them to the holes in the lower plate. Flow then leaves through holes in the lower plate to shower the area behind the combined impingement plate to destroy vortices, remove fouling accumulation, and exchange heat with the tube portions behind DPIP. A CFD simulation reflecting the flow distribution around the conventional impingement plate and the modified plate, DPIP, is discussed below showing the flow distribution improvement.

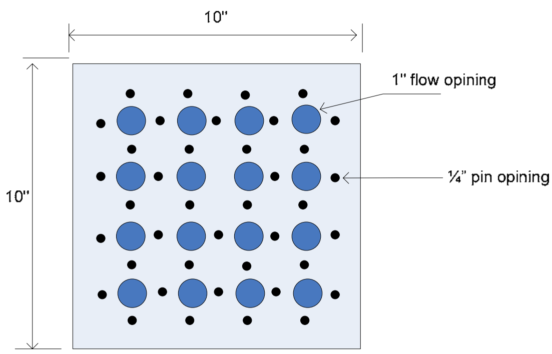

Fig. 5-a Top view of the Upper Plate with 25.4 mm (1") Flow Opining Holes and 6 mm (1/4") Pins Holes

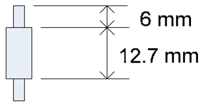

Fig. 5-b Type of Pins Holding the Two Plates

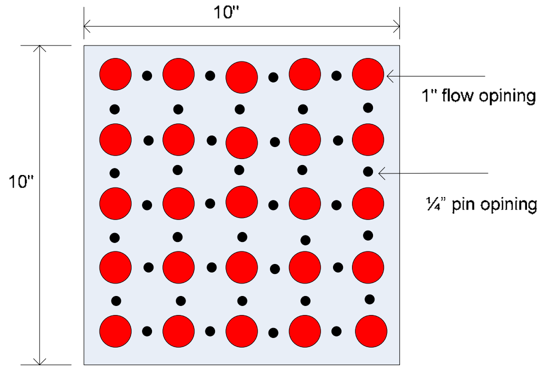

Fig. 5-c Top view of the Lower Plate with 25.4 mm (1") Flow Opining Holes and 6 mm (¼") Pins Holes

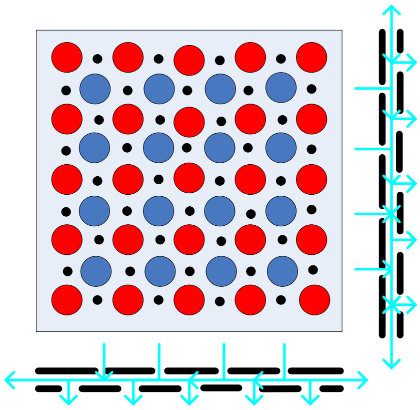

Fig. 6 Imagine Combination of the two Plates, DPIP, and Sides Views Flow

METHODOLOGY: NUMERICAL SUMULATION

CFD simulation of k-ε turbulence model of both conventional and modified plate was conducted based on the following data:

Equipment Data

As shown in Figure 7, the given dimensions for both heat exchanger with conventional and the modified impingement plate (DPIP) are listed in Table 2.

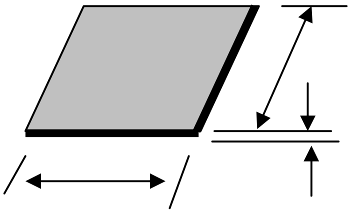

Figure 7-c Impingement Plate

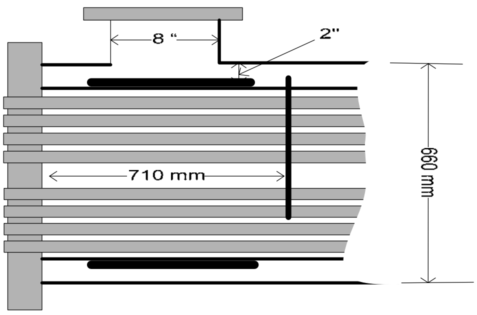

Fig. 7-a Conventional Impingement Plate Dimension

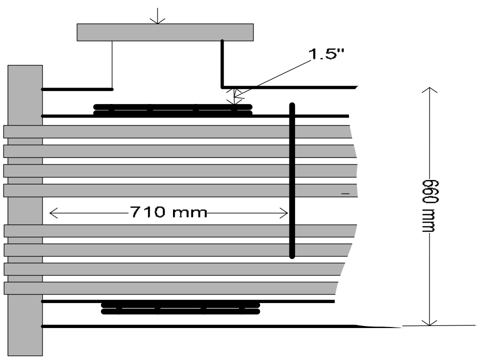

Fig. 7-b Modified Plate, DPIP, Dimension

Table 2. Equipment Parts Dimension

		Conventional	DPIP
Shell ID , Dz, mm		660	660
Inlet Span, mm		710	710
Plate Size	LxW, mm	Single 254x254	Double 254x254
	T, mm	Single 6	6 Each
	gap, mm(in)	0	12.7 (1/4)
Nozzle size , mm (in)		203.2 (8)	203.2 (8)
Distance between shell & Plate, mm (in)		50.8 (2)	32.1 (1.26)
Holes size in both plates, mm (in)		0	25.4 (1)
Holes number	Upper plate	NA	16
	Lower Plate	NA	25

The simplest form of impingement protection (Taborek, 1983) is a square or round plate located below the nozzle so that the escape flow area into the tube bundle is approximately equivalent to the nozzle area.

So the nozzle cross section area, Az, based on the inside diameter, Dz, equals to:

$$A_z = \frac{\pi D_z^2}{4} \text{...}(1)$$

The surface area of the cylindrical shape between the nozzle and the plate from the nozzle perimeter is called escape area, Ae, and equals to:

$$A_e = \pi D_z \times \frac{D_z}{4} \text{..}(2)$$

Since the nozzle inlet area equals the escape area so equation (1) and (2) are equal for conventional design.

For the modified design, DPIP, the distance between the nozzle and upper surface of DPIP need to be calculated. By applying the same concept, the holes in the upper plate are 16 holes of 25.4 mm (1") diameter, d_{uh}.

So the total cross section area of the 16 holes, A_{uh}, is:

$$A_{uh(tot)} = 16\frac{\pi d_{uh}^2}{4} \text{...}(3)$$

The inlet nozzle area must equal the escape area. So the nozzle area (Az) = total holes area (Auh(tot)) + surface area of the cylindrical shape between nozzle and upper plate (Ae). The difference between the nozzle area and the total holes area equals the surface area of the cylindrical shape between them.

So $$A_z - A_{uh(tot)} = \frac{\pi D_z^2}{4} - 16\frac{\pi d_{uh}^2}{4} = \pi D_z h \text{..........}(4)$$

By substituting for the holes diameter value of 1" in equation (4) and solve for (h) to have

$$h_1 = \frac{D_z^2 - 16}{4D_z} = \frac{64-16}{32} = 1.5''$$

So the minimum required distance, h, between the nozzle and the upper impingement plate DPIP for this nozzle size is 38 mm (1.5") instead of 50.8 mm (2") in the conventional design.

Shell Fluid Inlet Data

The shell side inlet fluid was assumed to be water at normal condition where the data tabulated in Table 3 were used to run the simulation.

Table 3. Shell Side Inlet Fluid

Inlet mass flow rate (kg/s)	Density (kg/m^3)
31.5	998.2

Computational Grid

Computation grids are created using the preprocessing software GAMBIT. Computational grids are divided into a large number of finite volumes. All the grids are unstructured type and have fine mesh at the walls and in the critical regions to capture the steep velocity gradients. The first grid point is set a reasonable distance above the viscous sub layer, which corresponds to y+ (dimensionless coordinate) of 60. Symmetric half of the heat exchanger is considered only, in computational modeling due to limitation in computational capabilities.

RESULT & DISCUSSION

The results from simulating the flow pattern at both cases, conventional and modified impingement plate, was conducted and showed promising results. The comparison between conventional plate and double perforated impingement plate, DPIP, shows the flow pattern improvement as per Figures 8 & 9. While fluid flows around DPIP, little flow passes through the offset holes to shower the tubes portion behind DPIP and stop fouling accumulation on the tubes. The simulation shows that the objective of the work to enhance flow pattern at the area downstream the impingement plate is achievable by using double perforated impingement plate.

Figure 8-a&b shows computational fluid dynamic of velocity contour for conventional impingement plate. The views are shown at a central cross section at shell inlet nozzle at front and side views. It is clear that there is a large stagnant area below the conventional plate. This stagnant area allows fouling accumulation and tube corrosion attack under conventional impingement plate.

Figure 9-a&b shows computational fluid dynamic of velocity contour for modified plate, double perforated impingement plate, DPIP through the same central front and side views. It is clear that the stagnant area under impingement plate was motivated by destroying the vortex movement at the area behind DPIP and allowing flow movement in that area. There is still an area of improvement of using Double Perforated Impingement Plate, DPIP.

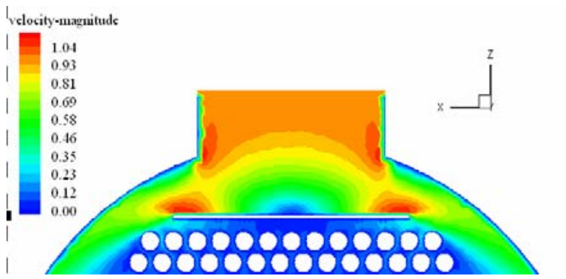

Figure 8-a Velocity contours at cross section across the tubes at conventional plate

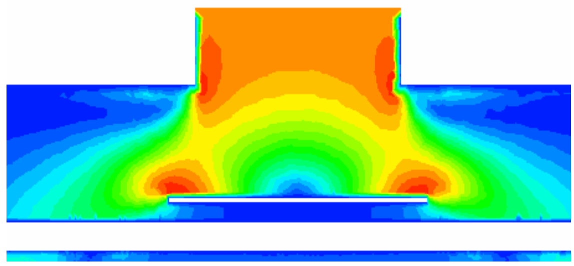

Figure 8-b Velocity contours at cross section along the tubes at conventional plate

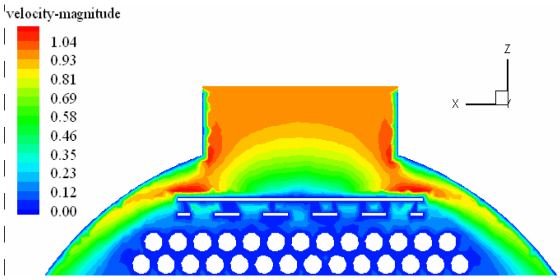

Figure 9-a Velocity contours at frontal cross section of the double perforated impingement plate 1-1inch.

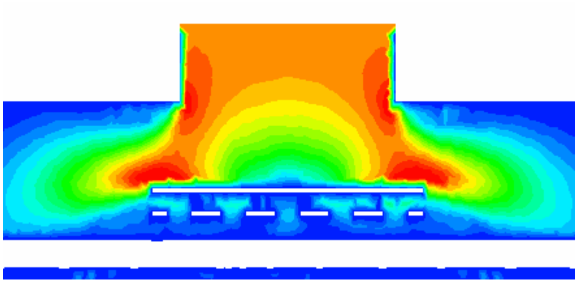

Figure 9-a Velocity contours at cross section along the tubes at the double perforated impingement plate 1-1inch.

After analyzing the result of the CFD work based on the data given in Table 2, it showed good achievement in improving the stagnant area behind impingement plate and protecting the tubes against under-deposit corrosion. But it was found there is an area of improvement.

By applying the continuity equation of steady condition of incompressible flow at fixed shape, we may then say that:

Total cross sectional area of the holes in the upper plate for entering flow = total area of leaving flow

So $\sum A_{uh} = \sum A_{lh} + \sum A_{g}$

- A_{uh}: cross section area of the holes in the upper plate
- A_{lh}: cross section area of the holes in the lower plate
- A_{g}: cross section area of the side opining, gap between the plates

From Table 2: the cross section area of the holes in the upper plate is $\sum A_{uh1}$ = 12.56 in^2

The cross section area of the holes in the lower plate is $\sum A_{lh1}$ = 19.62 in^2

The cross section area of the side opining, gap is

$\sum A_{g1}$ = 20 in^2

Results show exit area exceeds entrance area by 27 in^2 which might allow side flow entering into the gap between the plates due to low pressure. Moreover, the required distance, h1, between the nozzle and the upper plate is 38 mm (1.5") while the remaining distance after adding DPIP from the original height, h = 50.8 mm (2"), is only 32.1 mm (1.26 in). This height limitation may cause high velocity at the nozzle-plate edges, as shown in Figure 9, reflected in higher pressure drop.

Due to the previous two problems created by the proposed DPIP, back flow and high velocity at nozzle-plate edges, a new rearrangement of DPIP is then proposed with new parameters as shown in Table 4. The modified plate, DPIP, is turned up-down in the new proposal. Also, the size of the holes in the upper plate was increased to 38 mm (1.5 in) and the plates' sizes were also increased to 304.8x304.8 mm (12x12 in) to accommodate all the holes and avoid holes overlap.

Table 4. New DPIP Dimension

		Conventional	DPIP
Plate Size	LxW, mm	Single 254x254	Double 304.8x304.8
	t, mm	Single 6	6 Each
	gap, mm (in)	0	12.7 (1/4)
Nozzle size, mm (in)		203.2 (8)	203.2 (8)
Distance between shell & Plate, h, mm (in),		50.8 (2)	32.1 (1.26)
Holes size in both plates mm (in)		0	Upper plate: 38 (1.5) Lower Plate: 25.4 (1)
Holes number	Upper plate	NA	25
	Lower Plate	NA	16

The new recommended DPIP as per Table 4 is shown in Figure 10 for each plate. Also the combination is presented in Figure 11 with different views and expected flow distribution within the combination.

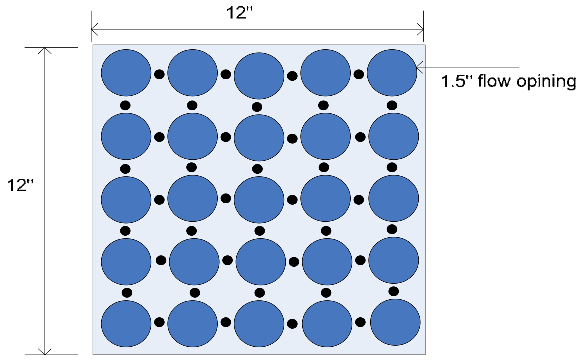

Figure 10-a: Top view of the Upper Plate with 38.1 mm (1.5") Flow Opining Holes and 6 mm (1/4") Pins Holes

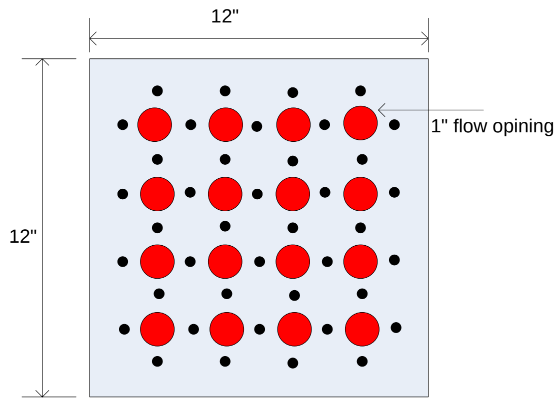

Figure 10-b: Top view of the Lower Plate with 25.4 mm (1") Flow Opining Holes and 6 mm (¼") Pins Holes

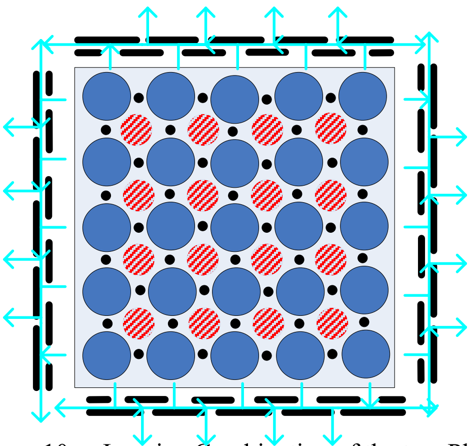

Figure 10-c: Imagine Combination of the two Plates, DPIP, of 38.1x25.4 mm Holes and Sides Views Flow

The new proposed modification of the double perforated impingement plate as per Table 4 results in the following dimension:

1. The minimum required distance, h, between the nozzle and the upper impingement plate DPIP for this nozzle size is 13.8 mm (0.54") instead of 50.8 mm (2") in the conventional design to be within the allowable height of 32.1 mm (1.26 in). This height can be calculated as per the following relation with considering the holes in the lower plate and the side opening is the controlling flow areas of the flow entering the plates arrangement:

$$h_2 = \frac{D_z^2 - Nd_{lh2}^2 - \frac{8L}{\pi}}{4D_z} = 0.54"$$

Maintaining the distance of 38 mm (1.5") between the upper plate and the nozzle, the velocity will decrease around the plate and accordingly, the vibration and erosion definitely will be reduced.

2. From Table 4: the cross section area of the holes in the upper plate is $\sum A_{uh2} = 44.16 \text{ in}^2$

The cross section area of the holes in the lower plate is $\sum A_{lh2} = 12.56 \text{ in}^2$

The cross section area of the side opining, gap is

$$\sum A_{g2} = 24 \text{ in}^2$$

The result is that the entrance area is more than the exit area by 7.6 in^2 which will give better flow pattern and flow distribution around and through DPIP.

Moreover, to have an idea about the flow around and leaving DPIP before entering the bundle and to be within the allowable values recommended by TEMA as per Table 1, the calculation in Table 5 is provided. The calculation is based on the data given in Table 3, and 4 along with the equipment dimensions given in Figure 7, with assuming same pressure balance at the bundle entrance since the plate occupies small space:

Table 5. Flow to Enter the Bundle

Flow Areas (m^2)		Velocity (m/s)	ρV^2 (kg/m.s^2)
Area around DPIP	0.156	0.175	30.5
Total holes in the lower plate	0.008	0.175	30.5
Gap between plates	0.016	0.175	30.5

CONCLUSIONS

As discussed in this paper a solution to a chronic problem causing repeated tube failure at shell-and-tube heat exchangers is presented in terms of using Double Perforated Impingement Plate to eliminate fouling accumulation on tubes surface downstream the impingement plate at exchanger inlet nozzle within the first tube rows due to low velocity and vortices production.

The simulation of the flow pattern using DPIP concluded the following:

1. Stagnation downstream impingement plate is eliminated by allowing small fluid leak through DPIP
2. The area for heat transfer is effective utilized
3. CFD analysis has proven better fluid dynamics within DPIP as compared to conventional impingement protection design
4. Velocity increase behind the plate maintains the tubes surface temperature within the mean design condition which prolongs the life of the tubes

NOMENCLATURE

A_e: escape surface area of the cylindrical shape between the nozzle and the upper surface of the impingement plate, $\pi D_z \times \frac{D_z}{4}$, m^2

A_g: cross sectional area of the side opining, gap between the plates, Lg, m^2

$A_{lh(tot)}$, A_{lh}: cross section area of the holes in the lower plate, $\frac{\pi d_{lh}^2}{4}$,m^2

$A_{uh(tot)}$,A_{uh}: Cross sectional area of the holes in the upper plates, $\frac{\pi d_{uh}^2}{4}$, m^2

Az,: nozzle cross section area based the inside diameter, $\frac{\pi D_z^2}{4}$, m^2

d_{lh}: holes diameter on the lower plate, m

d_{uh}: holes diameter on the upper plate, m

D_z: inside nozzle diameter, m

h: distance between the nozzle and upper plat

V: linear velocity of the fluid at shell inlet nozzle, m/s

ρ: fluid density entering shell side, Kg/m^3

Subscript

e: escape surface area of the cylindrical shape between the nozzle and the upper surface of the

g: gap between the two perforated plates

lh: holes in the lower plate

uh: holes in the upper plate

z,: shell inlet nozzle

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