International Journal of Technical Research and Applications e-ISSN: 2320-8163,
www.ijtra.com Volume 4, Issue 6 (Nov-Dec 2016), PP.114-124

ANALYTICAL STUDY OF TUBE BANKS HEAT EXCHANGER

Sandeep Saha
Student, Professor
Department Of Mechanical Engineering , Shri Shankaracharya Technical Campus , Shri Shankaracharya Group of Institutions ,
Faculty of Engineering and Technology, Junwani, Bhilai (C.G.) Pin-490020 ,India
[1] sandypsaha@gmail.com

Abstract— **A heat exchanger is a device which is designed to exchange heat efficiently from one medium to another. The basic component of a heat exchanger can be viewed as a type which consists of one fluid running through it and another fluid flowing by on the outside. There are three heat transfer operations that need to be described:**

- **Convective heat transfer from fluid to the inner wall of the tube.**
- **Conductive heat transfer through the tube wall.**
- **Convective heat transfer from the outer tube wall to outside fluid.**

Heat exchanger are classified according to type of construction and flow arrangement.

They are

I. Concentric tube type
II. Shell and tube type
III. Cross flow type

Tube banks are widely employed in cross flow heat exchangers, which are used in numerous services and industrial applications. Transfer of heat inflow across a bank of tubes is of a particular importance in design of heat exchangers. Analytical studies were performed to investigate the transfer of heat in cross flow tube banks under isothermal boundary condition.

Keywords— **Analytical Study, Banks Heat Exchanger, exchange heat efficiently.**

I. INTRODUCTION

A tube bank is a type of heat exchanger, a device that is designed as per need to allow fluids or gases to heat or cool. This heat exchanger design is very popular around the world and is employed in wide variety of locations. For various applications, numerous manufacturers produce tube banks for various applications and it is also possible to design a custom device and install for a specific setting or application with special requirement.The tube bank consists of an arrangement of tubes that are bathed in a fluid. Depending on desired effect, materials that regulates through tubes can be heated by the fluid as it radiates or can be cooled by fluid as it absorbs the heat. The efficiency of device varies according to number of tubes present and the size of tube bank.

Air conditioning, Refrigeration system and Radiators all use heat exchanger, all these can adapt tube banks. Tube banks are also used in industrial applications like chemical plants to heat or cool the materials for processing. Home heating systems rely on tube banks design and they can be adapted in solar water heating systems and many other settings.

Efficiency of heat exchanger is determined by the size of tubes. Small tubes are more efficient as there is less material to cool or heat. The materials used to make the tubes can vary, depending on materials being carried and setting. To operate the tube bank safety and successfully, it may be necessary to use non-corrosive, heat resistant materials or other specified materials. Over time, the lining of tubes can become clogged or foulded with materials that pass through. To operate properly; these devices used to be serviceable or clean them on regular basis. It may also be periodically necessary to replace tubes, depending upon the type of material being transported. It is especially important to make sure device is regularly checked for early sign of leaks.

II. PROBLEM IDENTIFICATION

A. Problem Identification

The present study deals with the investigation of heat transfer from tube banks in cross flow under isothermal boundary condition. For the calculation of average heat transfer from the tubes of a bank, wide range of parameters including longitudinal and transverse pitch, Reynolds number and Prandtl number ($\geqslant 0.71$)

B. Assumptions

The following assumptions are made in present work:

1. The flow is steady.
2. The flow is laminar.
3. The flow is fully developed.
4. Flow is two-dimensional.
5. The models for inline and staggered arrangement are applicable for use over a wide range of parameters when determining heat transfer from tube banks.

III. GOVERNING EQUATION

Energy integral equation for isothermal boundary condition

$$\frac{d}{ds}\int_0^{\delta T}(T - Ta).u.d\eta = -\alpha .\partial T/\partial \eta \Big|_{\eta=0} \qquad .(1)$$

Temperature Distribution

$\frac{(T-Ta)}{(Tw-Ta)} = A+ B.\eta_T+ C.\eta_T^2+D.\eta_T^3$

Using Isothermal Boundary Conditions presented by W.A.Khan,

Where A=1,B=-3/2,C=0,D=1/2

So, the temperature profile for Isothermal Pin will be

$\frac{(T-Ta)}{(Tw-Ta)}= 1- 3/2.\eta_T + 1/2.\eta_T^3$

By Rearranging

$(T-T_a) = (T_w-T_a) * (1- 3/2\eta_T + 1/2.\eta_T^3)$

Let $\eta_T = S/\delta_T$

$(T-T_a) = (T_w-T_a) * (1- 3/2.S/\delta_T + 1/2.S^3/\delta_T^3)$. (2)

Velocity Distribution

$\frac{u}{U(s)}= a.\eta_H+ b.\eta_H^2+c.\eta_H^3+d.\eta_H^4$

Applying hydrodynamic boundary conditions

a=2+λ/6 ,b=-λ/2 ,c=-2+λ/2 ,d=1-λ/6

So, the velocity profile inside the boundary layer will be

$\frac{u}{U(s)} = \{(2\eta_H- 2\eta_H^3+\eta_H^4)\}$

Let $\eta_H = s/\delta_H$

$d\eta_H = ds/\delta_H$

$\frac{u}{U(s)} = [(2s/\delta_H – 2s^3/\delta_H^3 + s^4/\delta_H^4) + \lambda/6(s/\delta_H – 3s^2/\delta_H^2 + 3s^3/\delta_H^3 + s^4/\delta_H^4)]$

$u = [(2s/\delta_H – 2s^3/\delta_H^3 + s^4/\delta_H^4) + \lambda/6(s/\delta_H – 3s^2/\delta_H^2 + 3s^3/\delta_H^3 + s^4/\delta_H^4)].U(s)$.(3)

Now, Putting the values of u and $(T-T_a)$ in (1)

Therefore equation (1) becomes,

Taking L.H.S,

$\frac{d}{ds}\int_0^{\delta T}[(T_w-T_a). (1-3/2.s/\delta_T+1/2.s^3/\delta_T^3)][(2s/\delta_H– 2s^3/\delta_H^3+s^4/\delta_H^4 \frac{\lambda}{6}(s/\delta_H - 3s^2/\delta_H^2 + 3s^3/\delta_H^3- s^4/\delta_H^4)]U(s)\frac{ds}{\delta H}$

Since, $\zeta=\delta_T/\delta_H$, Putting $\delta_T=\zeta .\delta_H$

- $\frac{d}{ds}\int_0^{\zeta.\delta H}[(T_w- T_a). (1-3/2.s/(\zeta.\delta_H)+ 1/2 .s^3/(\zeta^3.\delta_H^3)][(2 s/\delta_H–2s^3/\delta_H^3+ s^4/\delta_H^4)+ \frac{\lambda}{6}(s/\delta_H - 3s^2/\delta_H^2 + 3s^3/\delta_H^3- s^4/\delta_H^4)].U(s)\frac{ds}{\delta H}$
- $\frac{d}{ds}\int_0^{\zeta.\delta H}[(T_w-T_a).1/2.\zeta^3\delta_H^3.(2\zeta^3\delta_H^3 - 3s.\zeta^2.\delta_H^2+s^3)].[1/\delta_H^4(2s.\delta_H^3-2s^3\delta_H +S^4)+\frac{\lambda}{6}(s.\delta_H^3- 3s^2.\delta_H^2+3s^3.\delta_H -s4)].U(s) \frac{ds}{\delta H}$
- $\frac{d}{ds}\int_0^{\zeta.\delta H}[(T_w-T_a).1/2.\zeta^3\delta_H^7.(2\zeta^3\delta_H^3- 3s\zeta^2\delta_H^2+s^3)].[(2s.\delta_H^3-2s^3.\delta_H+s^4)+ \frac{\lambda}{6}(s.\delta_H^3- 3s^2\delta_H^2+3s^3.\delta_H -s^4)].U(s) \frac{ds}{dh}$
- $\frac{d}{ds}.(T_w-T_a)/2.\zeta^3.\delta_H^8\int_0^{\zeta.\delta H}.[\{4s\zeta^3\delta_H^6 - 4s^3\zeta^3\delta_H^6+2s^4\zeta^3\delta_H^3 -6s^2\zeta^2\delta_H^5 +6s\zeta^4\delta_H^2 - 3s^5\zeta^2\delta_H^2+2s^4\delta_H^3-2s^6\delta_H+s^7\}+\lambda/6\{2s\zeta^3\delta_H^6- 6s^2\zeta^3\delta_H^5+6s^3\zeta^3\delta_H^4-2s^4\zeta^3\delta_H^3 -3s^2\zeta^2\delta_H^5 +9s^3\zeta^2\delta_H^4- 9s^4\zeta^2\delta_H^3-3s^5\zeta^2\delta_H^2+s^4\delta_H^3-3s^5\delta_H^2+3s^6\delta_H -s^7\}].U(s)ds$

After integrating, we get

- $\frac{d}{ds}.U(s).(T_w-T_a)/2.\zeta^3.\delta_H^8.[\{2s^2\zeta^3\delta_H^6 -2s^3\zeta^2\delta_H^5 - s^4\zeta^3\delta_H^4+\frac{2}{5}s^5\zeta^3\delta_H^3+\frac{6}{5}s^5\zeta^2\delta_H^3- \frac{1}{2}s^6\zeta^2\delta_H^2 + \frac{2}{5}s^5\delta_H^3- \frac{2}{7}s^7\delta_H+s^8/8\}+\lambda/6\{s^2\zeta^3\delta_H^6-2s^3\zeta^3\delta_H^5+\frac{3}{2}s^4\zeta^3\delta_H^4- \frac{2}{5}s^5\zeta^3\delta_H^3-s^3\zeta^2\delta_H^5+\frac{9}{4}s^4\zeta^2\delta_H^4-\frac{9}{5}s^5\zeta^2\delta_H^3- \frac{1}{2}s^6\zeta^2\delta_H^2+\frac{1}{5}s^5\delta_H^3- \frac{1}{2}s^6\delta_H^2 + \frac{3}{7}s^7\delta_H - s^8/8\}]_o^{\zeta.\Delta h}$
- $\frac{d}{ds}.U(s).(T_w-T_a)/2.\zeta^3.\delta_{H8}.[(2\zeta_5\delta_{H8} - \frac{3}{35}\zeta_7\delta_H^8+\frac{1}{40}\zeta^7\delta_H^8)+\lambda/6(\frac{1}{5}\zeta^5\delta_H^8- \frac{1}{4}\zeta^6\delta_H^8+\frac{9}{70}\zeta^7\delta_H^8 - \frac{41}{40}\zeta^8\delta_H^8)]$
- $\frac{d}{ds}.U(s).(T_w-T_a)/2.[\zeta^8\delta_H \frac{2}{5} - \frac{3}{35}\zeta^2 \frac{1}{40}\zeta^3 \frac{\lambda}{6}(\frac{1}{5} - \frac{1}{4}\zeta + \frac{9}{70} \zeta^2 - \frac{41}{40}\zeta^3)\}]$

Since ζ<1,therefore higher order terms can be neglected

- $\frac{d}{ds}.U(S).(T_w-T_a)/2.\zeta^2[(\frac{2}{5} +\frac{\lambda}{6}(\frac{1}{5} - \frac{1}{4}\zeta)]$

- $d/ds.U(S)/2.\zeta.(T_w-T_a).[\zeta(2/5+\lambda/30)]$
- $d/ds.U(S)/2.\zeta.(T_w-T_a).[\zeta((\lambda+12)/30)]$

Taking R.H.S,

For $\delta T/\delta\eta$,

- $(T-T_a)/(T_w-T_a)= 1-3/2\eta_T+1/2\eta_T^3$
- $(T-T_a)=(T_w-T_a).(1-3/2\,\eta_T+1/2\eta_T^3)$

Differentiating both side

$\delta T/\delta\eta = (T_w-T_a).(3/2\eta_T^2-3/2)$

$\delta T/\delta\eta = (T_w-T_a).3/2.(\eta_T^2-1)$

Therefore, the equation becomes

$d/ds.U(s).[(\lambda+12)/30].\zeta^2= -\alpha.3.(\eta_T^2-1)$

$0\le\eta_T = \eta/\delta_T\le 1$

$\Delta T.d/ds.[U(s).\delta_T.\zeta.(\lambda+12)=90\alpha$
.(4)

Where U(s) is the potential flow velocity outside the boundary layer, and λ is the pressure gradient parameter given by;

$\lambda = \delta^2/\nu.\ dU(s)/ds$

By using complex variable theory, the potential flow velocity outside the boundary layer obtained was

$U(s)=U_{max}.f(0)$
.(5)

Where

$$f(\theta)=\sin\theta - 2\sin^2(\pi/2a)$$

$$X\ \frac{\{(\cosh(\pi/a\sin\theta)\sin\theta.....)}{(\cosh(\pi/a\sin\theta)-\cos[(\pi/a\cos\theta)])} + \frac{\pi}{a}\sin\theta)$$

$$X\ \frac{\sinh[(\pi/a\sin\theta)\sin\theta+\cos\theta\sin(\pi/a\cos\theta)]}{[\cosh(\pi/a\sin\theta)-\cos(\pi/a\cos\theta)]2\}}$$
.(6)

For an inline arrangement and

$$f(\theta)=\sin\theta-\frac{\pi}{2a})X\{\frac{(\cosh(\pi\sin\theta/2a)\sin\theta)}{(\cosh(\pi\sin\theta/2a)-\cos(\frac{\pi\cos\theta}{2a})}$$

$$-\sinh(\frac{\pi\sin\theta}{2a})X\frac{\sinh\left(\frac{\pi\sin\theta}{2a}\right)\sin\theta+\sin(\pi\cos\theta)/2a)\cos\theta}{\left[\cosh\left(\frac{\pi\sin\theta}{2a}\right)-\cos\left(\frac{\pi\cos\theta}{2a}\right)\right]2}$$

$$+\frac{\cosh\left(\pi\frac{\sin\theta-2h}{2a}\right)\sin\theta}{\cosh\left(\pi\frac{\sin\theta-2h}{2a}\right)-\cos(\pi\frac{\cos\theta-2a}{2a})}$$

$$-\ \sinh(\pi\frac{\sin\theta-2h}{2a})\frac{\sinh\left(\pi\frac{\sin\theta-2h}{2a}\right)\sin\theta+\sin\left(\pi\frac{\cos\theta-2a}{2a}\right)\cos\theta}{\left[\cosh\left(\pi\frac{\sin\theta-2b}{2a}\right)-\cos\left(\pi\frac{\cos\theta-2a}{2a}\right)\right]2}\}$$
.(7)

For staggered arrangement,

Using the definition of local and then average heat transfer coefficients C1 to obtain expressions of longitudinal and transverse pitch ratios for both inline and staggered arrangements.

$C_1=\{(0.25+\exp(-0.55\delta L)\}\delta T0.285\ \delta L0.212$
(for inline arrangement)

$C_1=((0.61\delta T\ 0.091\ \ \delta L\ 0.053)/(1-2\exp(-1.09\delta L))$

(for staggered arrangement)
.(8)

Above relation is valid for $1.05\le\delta L\le3$ and $1.05\le\delta T\le3$

The dimensionless heat transfer coefficient in terms of C1, ReD, and Pr numbers can be written as

$Nu_D=hD/k_f=C_1.Re_D^{1/2}.Pr^{1/3}$
.(9)

From (8) and (9), the present work proposes new equation for C1 as,

For Compact tube bank

$C_1 = 0.78x\ \delta_L^{0.091}\ x\ \ \delta_T^{0.053}/\{1-\exp(-1.09\delta_L)\}$

For Wide tube bank

$C_1 = 0.625\,x\ \delta_L^{0.091}\ x\ \delta_T^{0.053}\ /\{1-2\exp(-1.09\delta_L)\}$

4.RESULTS & DISCUSSION

Results obtained by solving the above equations requires certain values which are available in the table 4.1.In the present analysis tube banks are considered both compact and wide for both staggered and inline arrangements. Tube banks with $\delta T\ x\ \delta L\le\ 1.25\ x\ 1.25$ are considered compact and $\delta T\ x\ \delta L\le\ 2\ x\ 2$ are considered to be widely spaced.

In such cases are assumed to be steady state conditions , with negligible radiation effects, and negligible effect of change in air temperature on air properties.Then the following given data is used to calculate air-side convection coefficient.

Table 4.1 - Data used by Incropera and DeWitt (31) for staggered tube bank

Quantity	**Dimension**
Tube Diameter (mm)	16.4
Longitudinal pitch (mm)	20.5, 34.3
Transverse pitch (mm)	20.5, 31.3
Number of tubes (Staggered)	8×7
Approach velocity (m/s)	6
Thermal conductivity of air (W/m K)	0.0253
Density of air (kg/m^3)	1.217
Specific heat of air (J/kg K)	1007
Kinematic viscosity (m^2/s)	14.82×10^{-6}
Prandtl number (Air)	0.701
Ambient temperature (°C)	15
Tube surface temperature (°C)	70
Length of tube (L)	10^{-3}m

Table 4.2 - Comparison of results for compact tube bank (1.25×1.25)

	NuD	**h (W/m2K)**	**T. (°C)**	**(kW)**
Incropera and Dewitt [31]	152.0	234.0	38.5	28.4
Present analysis	196.1	302.5	43.3	34.1

Table 4.3 Comparison of results for wide tube bank (2.1 × 2.1)

	NuD	**h (W/m2K)**	**T. (°C)**	**Q(kW)**
Incropera and Dewitt [31]	87.9	135.6	25.5	19.4
Present analysis	88.3	136.2	26.9	19.2

Table 4.2 and 4.3 are very important to understand the reason behind the variation of data at the given condition. By looking to the table, we observe increase in heat transfer coefficient with the increase in temperature in case of compact tube banks whereas in the case of wide tube banks we observe decrease in heat transfer coefficient with increase in temperature. These data are also used to solve the eq. 8 & 9 to find the value of C1 for various arrangements.

From New C1 Relation,

1) Uapp=5m/s

Table 4.4 Staggered arrangement for compact tube bank for Uapp=5m/s

Arrangement	C_1	Umax	Nu_D	h
1.25 x 1.25	1.276	25	188.53	290.84
1.24 x 1.24	1.304	25.83	195.70	301.90
1.23 x 1.23	1.317	26.74	201.24	310.5
1.22 x 1.22	1.329	27.72	206.76	318.96
1.21 x 1.21	1.347	28.81	213.64	329.57
1.20 x 1.20	1.358	30	219.79	339.06

The Results in Table 4.4 shows the increase in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with decrease in the size of the arrangement.

2) Uapp=6m/s

Table 4.5 Staggered arrangement for compact tube bank for Uapp =6m/s

Arrangement	C_1	Umax	Nu_D	h
1.25 x 1.25	1.276	30	206.52	318.59
1.24 x 1.24	1.304	30.96	214.04	330.75
1.23 x 1.23	1.317	32.08	220.42	340.04
1.22 x 1.22	1.329	33.27	226.51	349.43
1.21 x 1.21	1.347	34.57	234.02	361.01
1.20 x 1.20	1.358	36	240.77	371.43

The Results in Table 4.5 shows the increase in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with decrease in the size of the arrangement.

3) Uapp=7m/s

Table 4.6 Staggered arrangement for compact tube bank for Uapp=7m/s

Arrangement	C_1	Umax	Nu_D	H
1.25 x 1.25	1.276	35	223.07	344.12
1.24 x 1.24	1.304	36.16	231.72	357.48
1.23 x 1.23	1.317	37.43	238.10	367.31
1.22 x 1.22	1.329	38.81	244.66	377.43
1.21 x 1.21	1.347	40.33	252.78	389.96
1.20 x 1.20	1.358	42	260.06	401.19

The Results in Table 4.6 shows the increase in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with decrease in the size of the arrangement.

1) Uapp=5m/s

Table 4.7 Staggered Arrangement for Wide Tube bank

Arrangement	C_1	Umax	Nu_D	h
2.1 x 2.1	0.862	9.54	78.57	121.36
2.2 x 2.2	0.85	9.16	76.02	117.27
2.3 x 2.4	0.838	8.84	73.62	113.57
2.4 x 2.4	0.827	8.57	71.54	110.36
2.5 x 2.5	0.818	8.33	69.76	107.61
2.6 x 2.6	0.810	8.125	68.22	105.24

The Results in Table 4.7 shows the decrease in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with increase in the size of the arrangement.

2) Uapp=6m/s

Table 4.8 Staggered Arrangement for Wide Tube bank

Arrangement	C_1	Umax	Nu_D	h
2.1 x 2.1	0.862	11.45	86.19	132.96
2.2 x 2.2	0.85	11	83.30	128.50
2.3 x 2.3	0.838	10.61	80.66	124.34
2.4 x 2.4	0.827	10.288	78.38	120.90
2.5 x 2.5	0.818	10	76.44	117.92
2.6 x 2.6	0.810	9.75	74.73	115.30

The Results in Table 4.8 shows the decrease in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with increase in the size of the arrangement.

3) Uapp=7m/s

Table 4.9 Staggered Arrangement for Wide Tube bank

Arrangement	C_1	Umax	Nu_D	h
2.1 x 2.1	0.870	13.36	93.38	144.06
2.2 x 2.2	0.85	12.83	89.96	138.78
2.3 x 2.3	0.838	12.38	87.12	134.41
2.4 x 2.4	0.827	12	84.68	130.63
2.5 x 2.5	0.818	11.66	82.54	127.33
2.6 x 2.6	0.810	11.375	80.72	124.52

The Results in Table 4.9 shows the decrease in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with increase in the size of the arrangement

1) Uapp=5m/s

Table 4.10 Inline arrangement for compact tube bank for Uapp=5m/s

Arrangement	C_1	Umax	Nu_D	h
1.25 x 1.25	1.076	25.00	158.98	245.25
1.24 x 1.24	1.075	25.83	161.44	249.05
1.23 x 1.23	1.074	26.74	164.94	253.16
1.22 x 1.22	1.073	27.72	166.94	257.53
1.21 x 1.21	1.072	28.81	170.03	262.30
1.20 x 1.20	1.070	30.00	173.18	267.16

The Results in Table 4.10 shows the increase in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with decrease in the size of the arrangement.

2) Uapp=6m/s

Table 4.11 Inline arrangement for compact tube bank for Uapp=6m/s

Arrangement	C_1	Umax	Nu_D	h
1.25 x 1.25	1.076	30.00	174.15	268.25
1.24 x 1.24	1.075	31.00	176.87	272.85
1.23 x 1.23	1.074	32.08	179.75	277.30
1.22 x 1.22	1.073	33.27	182.69	282.14
1.21 x 1.21	1.072	34.57	186.25	287.32
1.20 x 1.20	1.070	36.00	189.71	292.66

The Results in Table 4.11 shows the increase in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with decrease in the size of the arrangement.

3)Uapp=7m/s

Table 4.12 Inline arrangement for compact tube bank for Uapp=7m/s

Arrangement	C_1	Umax	Nu_D	h
1.25 x 1.25	1.076	35	188.11	290.19
1.24 x 1.24	1.075	36.16	191.02	294.68
1.23 x 1.23	1.074	37.43	194.16	299.52
1.22 x 1.22	1.073	38.81	197.53	304.72
1.21 x 1.21	1.072	40.33	201.17	310.34
1.20 x 1.20	1.070	42.00	204.91	316.11

The Results in Table 4.12 shows the increase in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with decrease in the size of the arrangement.

1) Uapp=5m/s

Table 4.13 Inline arrangement for wide tube bank for Uapp=5m/s

Arrangement	C_1	Umax	Nu_D	h
2.1 x 2.1	0.863	9.54	78.76	121.50
2.2 x 2.2	0.858	9.16	77.18	119.06
2.3 x 2.3	0.853	8.84	74.94	115.60
2.4 x 2.4	0.848	8.57	73.35	113.15
2.5 x 2.5	0.843	8.33	71.89	110.90
2.6 x 2.6	0.838	8.12	70.58	109.88

The Results in Table 4.13 shows the decrease in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with increase in the size of the arrangement.

2)Uapp=6m/s

Table 4.14 Inline arrangement for wide tube bank for Uapp=6m/s

Arrangement	C_1	Umax	Nu_D	h
2.1 x 2.1	0.863	11.45	86.29	133.12
2.2 x 2.2	0.858	11.00	84.09	129.72
2.3 x 2.3	0.853	10.61	82.10	126.65
2.4 x 2.4	0.848	10.28	80.37	123.98
2.5 x 2.5	0.843	10.00	78.77	121.51
2.6 x 2.6	0.838	9.75	77.32	119.28

The Results in Table 4.14 shows that decrease in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with increase in the size of the arrangement.

3)Uapp=7m/s

Table 4.15 Inline arrangement for wide tube bank for Uapp=7m/s

Arrangement	C_1	Umax	Nu_D	h
2.1 x 2.1	0.863	11.45	86.29	133.12
2.2 x 2.2	0.858	11.00	84.09	129.72
2.3 x 2.3	0.853	10.61	82.10	126.65
2.4 x 2.4	0.848	10.28	80.37	123.98
2.5 x 2.5	0.843	10.00	78.77	121.51
2.6 x 2.6	0.838	9.75	77.32	119.28

The Results in Table 4.15 shows the decrease in the values of Maximum velocity, Nusselt number and avg. heat transfer coefficient with increase in the size of the arrangement.

Variation of Tw at Uapp= 5m/s

Table 4.16 Compact tube bank for Uapp= 5m/s at Tw=70oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	36.56	43.33	13.50
6x5	6	40.42	38.45	17.97
8x7	8	46.90	36.80	32.10
9x8	9	49.59	34.90	39.14
10x9	10	52.015	33.137	46.45

The Results in Table 4.16 shows that for compact tube bank which indicates increase in the values of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.17 Wide tube bank for Uapp=5m/s at Tw=70oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	21.875	51.69	7.25
6x5	6	23.47	50.72	10.67
8x7	8	26.5	49.14	19.30
9x8	9	27.925	48.22	24.35
10x9	10	29.3	47.50	29.88

The Results in Table 4.17 shows that for wide tube bank which indicates increase in the values of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.18 Compact tube bank for Uapp=5m/s at Tw=100oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	48.15	67.105	20.90
6x5	6	54.27	63.34	29.60
8x7	8	64.30	56.83	49.57
9x8	9	68.55	53.87	60.42
10x9	10	78.205	51.21	71.79

The Results in Table 4.18 shows that for compact tube bank which indicates increase in the values of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.19 Wide Tube bank for Uapp=5m/s at Tw=100oC

Arrangement	N_T	T_o	ΔT	Total heat transfer
5x4	5	25.62	79.85	11.20
6x5	6	28.09	78.38	16.50
8x7	8	32.765	75.91	29.81
9x8	9	34.975	74.56	37.65
10x9	10	37.10	73.66	46.49

The Results in Table 4.19 shows that for wide tube bank which indicates increase in the values of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.20Compact tube bank for Uapp= 5m/s at Tw=200oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	87.15	146.44	45.68
6x5	6	100.47	137.85	64.42
8x7	8	122.30	124.76	108.83
9x8	9	131.55	117.25	131.50
10x9	10	139.40	111.46	156.26

The Results in Table 4.20 shows that for compact tube bank which indicates increase in the values of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.21 Wide tube bank for Uapp=5m/s at Tw=200oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	38.12	173.83	24.38
6x5	6	44.60	170.11	35.79
8x7	8	53.66	165.23	64.89
9x8	9	58.47	162.82	82.22
10x9	10	63.10	159.80	100.87

The Results in Table 4.21 shows that for wide tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Variation of Tw for Uapp = 6m/s

Table 4.22 Compact tube bank for Uapp=6m/s at Tw=70oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	33.64	45.03	14.03
6x5	6	37.22	42.73	19.97
8x7	8	43.54	38.99	34.01
9x8	9	45.96	37.39	41.93
10x9	10	48.33	35.80	50.19

The Results in Table 4.22 shows that for compact tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.23Wide tube bank for Uapp=6m/s at Tw=70oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	20.83	52.05	7.30
6x5	6	22.15	51.07	10.74
8x7	8	24.73	50.18	19.71
9x8	9	26.00	49.32	24.90
10x9	10	27.21	48.64	30.70

The Results in Table 4.23 shows that for wide tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.24Compact tube bank for Uapp=6m/s at Tw=100oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	43.81	69.00	21.68
6x5	6	49.34	66.42	31.03
8x7	8	58.77	60.50	52.77
9x8	9	62.85	57.65	64.66
10x9	10	66.51	55.32	77.55

The Results in Table 4.24 shows that for compact tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.25Wide tube bank for Uapp=6m/s at Tw=100oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	24.01	80.44	11.28
6x5	6	26.05	78.93	16.60
8x7	8	30.04	77.55	30.46
9x8	9	32.00	76.23	38.49
10x9	10	33.87	75.18	47.45

The Results in Table 4.25 shows that for wide tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.26Compact tube bank for Uapp=6m/s at Tw=200oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	77.7	152.92	47.64
6x5	6	89.0	144.81	67.67
8x7	8	110.27	131.77	114.95
9x8	9	119.15	126.55	141.93
10x9	10	127.11	120.42	168.83

The Results in Table 4.26 shows that for compact tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.27Wide tube bank for Uapp=6m/s at Tw=200oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	34.60	175	24.55
6x5	6	39.05	171.78	36.14
8x7	8	47.74	168.78	66.29
9x8	9	52.00	165.92	83.79
10x9	10	56.07	163.62	103.28

The Results in Table 4.27 shows that for wide tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Variation of Tw at Uapp= 7m/s

Table 4.28Compact tube bank for Uapp=7m/s at Tw=70oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	31.44	46.32	14.43
6x5	6	34.69	44.44	20.76
8x7	8	40.41	40.99	35.75
9x8	9	43.05	39.32	44.10
10x9	10	45.25	37.90	53.13

The Results in Table 4.28 shows that for compact tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.29Wide tube bank for Uapp=7m/s at Tw=70oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	19.95	52.66	7.38
6x5	6	21.21	51.93	10.92
8x7	8	23.47	50.72	19.92
9x8	9	24.57	50.36	25.43
10x9	10	25.67	49.62	31.32

The Results in Table 4.29 shows that for wide tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.30Compact tube bank for Uapp=7m/s at Tw=100oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	40.415	71.54	22.29
6x5	6	45.60	69.54	32.50
8x7	8	54.10	64.10	55.91
9x8	9	58.35	61.05	68.47
10x9	10	61.75	58.58	82.13

The Results in Table 4.30 shows that for compact tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.31Wide tube bank for Uapp=7m/s at Tw=100oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	22.65	81.38	11.41
6x5	6	25.20	80.31	16.89
8x7	8	28.09	78.38	30.78
9x8	9	29.79	77.84	39.30
10x9	10	31.49	76.70	48.41

The Results in Table 4.31 shows that for wide tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.32Compact tube bank for Uapp=7m/s at Tw=200oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	70.315	155.81	48.54
6x5	6	81.23	149.50	69.86
8x7	8	100.47	137.85	120.25
9x8	9	108.98	132.36	148.45
10x9	10	116.75	127.19	178.31

The Results in Table 4.32 shows that for compact tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.33Wide tube bank for Uapp=7m/s at Tw=200oC

Arrangement	N_T	T_o	ΔT_{lm}	Total heat transfer
5x4	5	31.65	177.13	24.86
6x5	6	35.90	174.16	36.64
8x7	8	43.49	170.60	67.00
9x8	9	47.19	168.53	85.10
10x9	10	50.70	166.84	105.31

The Results in Table 4.33 shows that for wide tube bank which indicates increase in the value of total heat transfer with increase in total number of tubes in the arrangement.

Table 4.34Variation of heat transfer parameter with transverse pitch for Inline Arrangement
in compact tube bank and wide tube bank

δ_TXδ_L	New C_1(compact)	δ_TXδ_L	New C_1(wide)
1.25 X 1.25	1.27	2.1 x 2.1	0.81
1.24 X 1.24	1.30	2.2 x2.2	0.81
1.23 X 1.23	1.31	2.3 x 2.3	0.80
1.22 X 1.22	1.32	2.4 x 2.4	0.79
1.21 X 1.21	1.34	2.5 x 2.5	0.79
1.20 X1.20	1.35	2.6 x 2.6	0.78

The Results in Table 4.34 shows that for Inline arrangement which indicates in increase of value of new C1 for compact with decrease in size of the arrangement whereas decrease in value of new C1 for wide with increase in size of the arrangement.

Table 4.35Variation of heat transfer parameter with transverse pitch for Staggered arrangement in compact tube bank and wide tube bak

δ_TXδ_L	NewC_1(compact)	δ_TXδ_L	NewC_1(wide)
1.25 X 1.25	1.30	2.1 x 2.1	0.85
1.24 X 1.24	1.30	2.2 x2.2	0.83
1.23 X 1.23	1.32	2.3 x 2.3	0.82
1.22 X 1.22	1.33	2.4 x 2.4	0.81
1.21 X 1.21	1.34	2.5 x 2.5	0.80
1.20 X1.20	1.36	2.6 x 2.6	0.79

The Results in Table 4.35 shows that for Staggered arrangement which indicates in increase of value of new C1 for compact with decrease in size of the arrangement whereas decrease in value of new C1 for wide with increase in size of the arrangement.

Comparison of NuD and ReD for both arrangements of compact tube bank

IV. STAGGGERED ARRANGEMENT

Table 4.36 Comparison of NuD and ReD of compact tube bank for staggered

δ_TX δ_L	Nu_D	Re_D
1.25 X 1.25	210.25	33198
1.24 X 1.24	214.25	34305
1.23 X 1.23	220.51	35506
1.22 X 1.22	226.70	36817
1.21 X 1.21	233.34	38255
1.20 X1.20	240.77	39838

The Results in Table 4.36 shows that for Staggered arrangement which indicates in increase in value of Nusselt number and Reynolds number with decrease in size of arrangement.

V. INLINE ARRANGEMENT

Table 4.37 Comparison of NuD and ReD of compact tube bank for inline

δ_TX δ_L	Nu_D	Re_D
1.25 X 1.25	136.28	33198
1.24 X 1.24	138.21	34305
1.23 X 1.23	140.81	35522
1.22 X 1.22	143.17	36817
1.21 X 1.21	145.77	38255
1.20 X1.20	148.75	39838

The Results in Table 4.37 shows that for inline arrangement which indicates in increase in value of Nusselt number and Reynolds number with decrease in size of arrangement.

Comparison of NuD andReD both arrangements of wide tube bank

VI. STAGGERED ARRANGEMENT

Table 4.38 Comparison of NuD and ReD of wide tube bank for staggered

δ_TX δ_L	Nu_D	Re_D
2.1 X 2.1	86.23	12670
2.2 X 2.2	82.52	12172
2.3 X 2.3	79.87	11741
2.4 X 2.4	77.66	11375
2.5 X 2.5	75.65	11066
2.6 X 2.6	73.95	10789

.The Results in Table 4.38 shows that for Staggered arrangement which indicates in decrease in value of Nusselt number and Reynolds number with increase in size of arrangement.

VII. INLINE ARRANGEMENT

Table 4.39 Comparison of NuD and ReDof wide tube bank for inline

δ_TX δ_L	Nu_D	Re_D
2.1 X 2.1	81.59	12670
2.2 X 2.2	79.38	12172
2.3 X 2.3	77.38	11741
2.4 X 2.4	75.50	11375
2.5 X 2.5	74.009	11066
2.6 X2.6	72.43	10789

The Results in Table 4.39 shows that for Inline arrangement which indicates in decrease in value of Nusselt number and Reynolds number with increase in size of arrangement.

Fig. 4.1 Variation of Tw=70˚C at Uapp= 5m/s

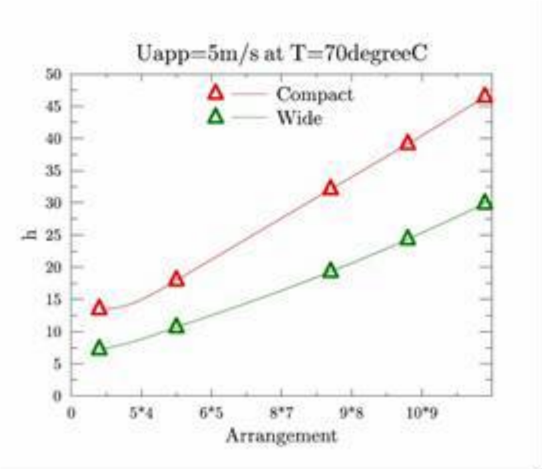

Fig. 4.1 shows the variation of Tw=70˚C , Uapp= 5m/s for various arrangements which indicates Compact tube banks has higher heat transfer rates than widely spaced ones.

Fig. 4.2 Variation of Tw= 100˚C at Uapp= 5m/s

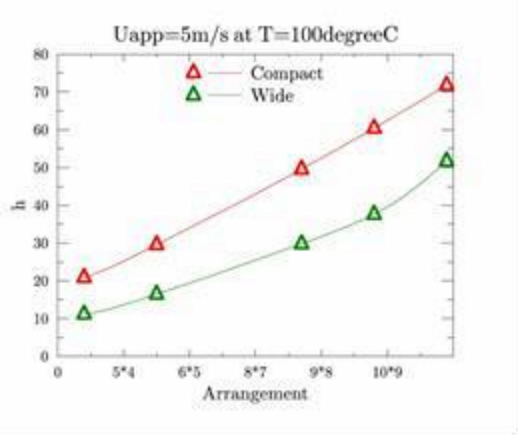

Fig. 4.2 shows the variation of Tw=100˚C , Uapp= 5m/s for various arrangements which indicates Compact tube banks has higher heat transfer rates than widely spaced ones.

Fig. 4.3 Variation of Tw=200˚C for Uapp = 5m/s

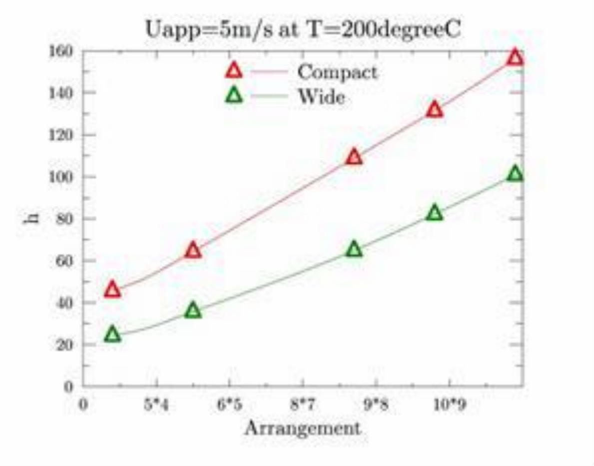

Fig. 4.3 shows the variation of Tw=200˚C , Uapp= 5m/s for various arrangements which indicates Compact tube banks has higher heat transfer rates than widely spaced ones.

Fig. 4.4 Variation of Tw=70˚C for Uapp = 6m/s

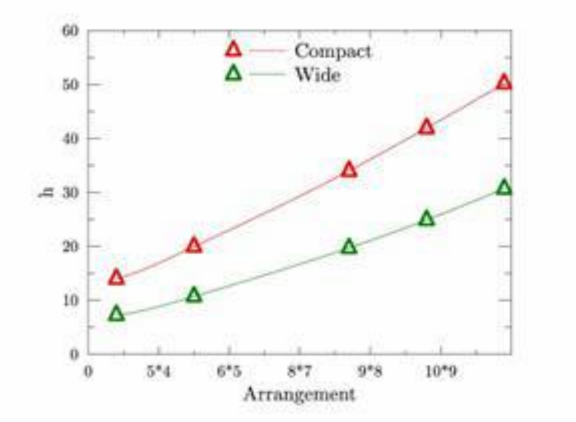

Fig. 4.4 shows the variation of Tw=70˚C , Uapp= 5m/s for various arrangements which indicates Compact tube banks has higher heat transfer rates than widely spaced ones.

Fig. 4.5 Variation of Tw=100˚C for Uapp = 6m/s

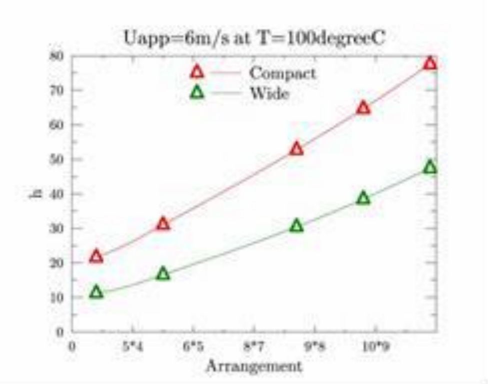

Fig. 4.5 shows the variation of Tw=100˚C , Uapp= 6m/s for various arrangements which indicates Compact tube banks has higher heat transfer rates than widely spaced ones.

Fig. 4.6 Variation of Tw=200˚C for Uapp = 6m/s

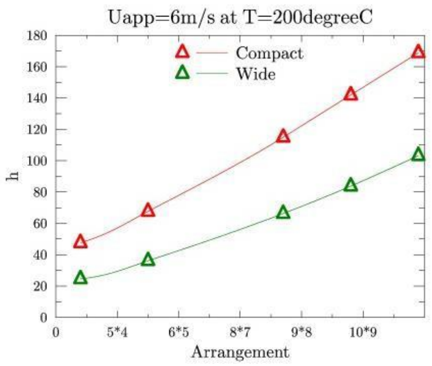

Fig. 4.6 shows the variation of Tw=200˚C , Uapp= 6m/s for various arrangements which indicates Compact tube banks has higher heat transfer rates than widely spaced ones.

Fig. 4.7 Variation of Tw=70˚C at Uapp= 7m/s

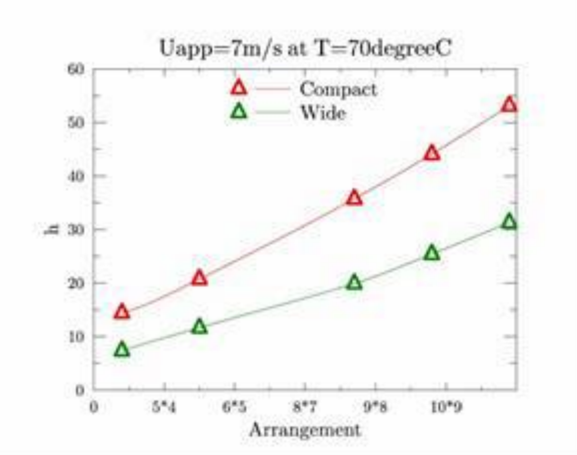

Fig. 4.7 shows the variation of Tw=70˚C , Uapp= 7m/s for various arrangements which indicates Compact tube banks has higher heat transfer rates than widely spaced ones.

Fig. 4.8 Variation of Tw=100˚C at Uapp= 7m/s

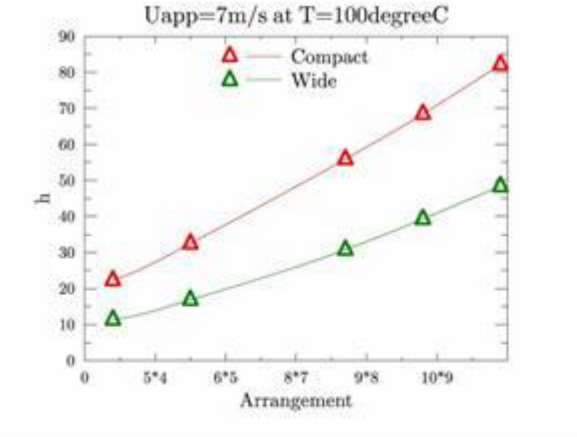

Fig. 4.8 shows the variation of Tw=100˚C , Uapp= 5m/s for various arrangements which indicates Compact tube banks has higher heat transfer rates than widely spaced ones.

Fig. 4.9 Variation of Tw=200˚C at Uapp= 7m/s

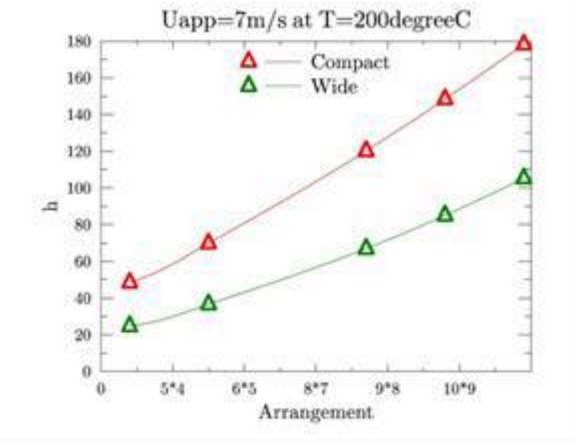

Fig. 4.9 shows the variation of Tw=200˚C , Uapp= 7m/s for various arrangements which indicates Compact tube banks has higher heat transfer rates than widely spaced ones

Fig. 4.10 NuDVsReDFor inline arrangement.

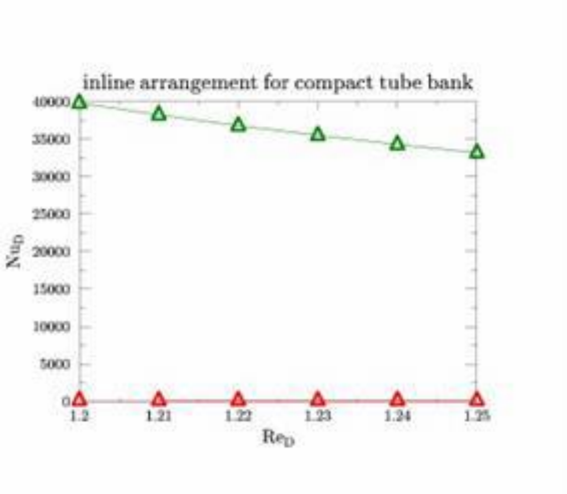

Fig.4.10 shows the values of Nusselt number and Reynolds number for various arrangements which indicates Nusselt number decreases but Reynolds number remains constant with increase in size of the arrangement.

Fig. 4.11 C1 Vs New C1

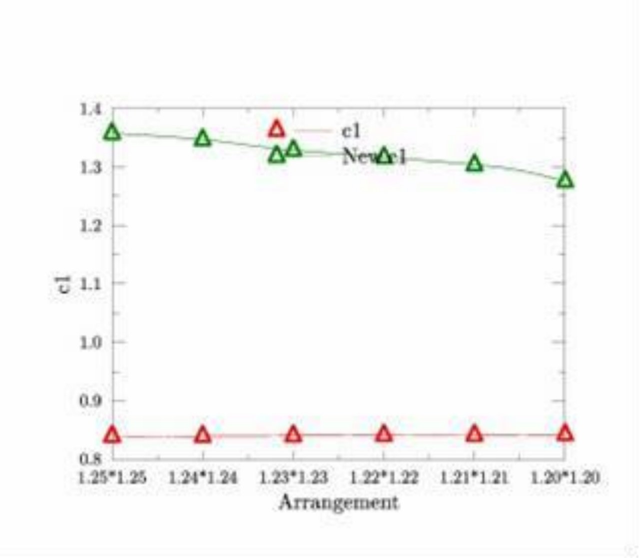

Fig.4.11 shows the values of C1 and new C1 for various arrangements which indicates New C1 decreases but C1 remains constant with deccrease in size of the arrangement.

CONCLUSIONS

Heat transfer from tube banks in cross flow is investigated analytically and (compact & wide) simplified models of heat transfer for (inline and staggered) both arrangements are presented. The important conclusions can be summarized as follows:

- The tubes may be arranged in in-line or staggered pattern, the total heat transfer rate from the tube bank depends upon average heat transfer coefficient, the inlet and outlet temperature, and the total heat transfer area .

$Q=h.A.\Delta Tlm$
Where $A=N\pi DL$,
Therefore, $Q=h.(N\pi DL).\Delta Tlm$

- Both models (inline or staggered) can be applied among a wide range of parameters and are suitable in design of tube banks.
- The average heat transfer coefficients (for tube banks in cross flow) depend on the longitudinal (δL) and transverse pitches (δT), Reynolds(ReD) and Prandtl number (Pr).
- Compact banks (in-line or staggered) shows higher heat transfer rates as compared to widely spaced ones.
- Heat transfer rates are higher for staggered arrangement as compared to inline arrangement.
- New C1 equation has been formulated.

REFERENCES

[1] D.Murray, Comparison of heat transfer is staggered and inline tube banks with gas-particle cross flow.Exp.Ther.Fluid Sci. 6(2) (1993) 177-185

[2] V.K.Mandhani,R.P.Chhabra,V.Eshwaran, Forced convection heat transfer in tube banks in cross flow., Chem. Eng. Sci.57(2002) 379-391.

[3] B.E.Launder and T.H.Massey, The numerical prediction of viscous flow and heat transfer in tube banks., Energy Procedia 17 (2012) 741-749

[4] He FaJiang, Cao Weiwu& Yan Ping, Experimental Investigation of heat transfer and flowing resistance for air flow crossover Spiral finned tube Heat exchanger.Energy Procedia 17 (2012) 741-749

[5] Tahseen Ahmed Tahseen, M.M.Rahman and M.Ishak, Experimental Study on Heat transfer and Friction factor in Laminar forced convection over flat tube in channel flowProcedia Engineering 105(2015) 46-55.

[6] S.B.Beale&D.B.Spadling, A numerical study of Unsteady fluid flow in Inline and Staggered Tube BanksJ.Fluidsstruct. 13 (1999) 713-754.

[7] W.A.Khan, J.R.Culham, M.M.Yuvanovich, Convection heat transfer from tube banks in Cross flow : Analytical approach.IJHMT 49 (2006) 4831-4838.

[8] 8) Tahseen Ahmed Tahseen, M.Ishak, M.M.Rahman, An overview on thermal and fluid flow characteristics in a plain plate finned and unfinned tube banks heat exchanger.Volume 43,March 2015, Pages 363-380.

[9] Xiaoqin Liu, Jianlin Yu, Gang Yan, A numerical study on the air side heat transfer of perforated finned tube heat exchanger with large fin pitches,Volume 100, September 2016,Pages 199-207..

[10] Ye Wang, Liang-Chen Wang, Zhi-Min Lin, Yu-Huan Yao, Liang-Bi Wang, The condition requiring conjugate numerical method in study of heat transfer characteristics of tube bank fin heat exchanger.IJHMT,Volume 55,Issues 9-10,April 2012,Pages 2353-2364

[11] A.V.de Poula, L.A.M Endres, S.V.Moller, Bisable features of the turbulent flow in tube banks of triangular arrangement..IJHMT, Volume 55,Issues 9-10,April 2012,Pages 2353-2364.

[12] W.A.Khan, Modelling of fluid flow & heat transfer for optimization of Pin-Fin Heat sinks.,Ph.D Thesis, University of Waterloo, Canada 2004.