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# A NUMERICAL STUDY ON A CERAMIC MONOLITH HEAT EXCHANGE WITH DIFFERENT CROSS SECTIONS

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## ABSTRACT

*Energy is one of the most important components of economic growth. But day by day the existing energy resources are depleting at alarming rate. Hence it is necessary to introduce alternate techniques to conserve the energy effectively. With this an attempt has been made to introduce a ceramic heat exchanger with different cross sections.*

*In this project Ceramic heat exchanger of varying tubes were simulated by computational fluid dynamics method (CFD). The multi shaped structure was imported in to ANSYS fluent 15.0 versions as a physical model. A ceramic monolith heat exchanger is designed to find out the performance and effectiveness of heat transfer. The numerical computation was performed throughout the domain including fluid region in exhaust gas side, ceramic core and fluid region in air side. The entire computation was carried out by using different cross sections viz., Rectangular, Elliptical and Cylindrical duct with air and exhaust in cross flow direction. After comparison of different tubes it is observed that the estimated heat transfer rate in cylindrical tube is 10% more than the rectangular and elliptical tubes.*

***KEYWORDS: Ceramic heat exchangers, CFD, Effectiveness, Heat transfer rates, pressure drop.***

## I.INTRODUCTION

A heat exchanger is a device that is used to transfer thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact.

Heat exchangers are important engineering devices in many process industries since the efficiency and economy of the process largely depend on the performance of the heat exchangers. The fluids may be separated by a solid wall to prevent mixing or they may be in direct contact. They are widely used in space heating, refrigeration, air conditioning, power stations, chemical plants, petrochemical plants, petroleum refineries, natural-gas processing, and sewage treatment. The classic example of a heat exchanger is found in an internal combustion engine in which a circulating fluid known as coolant flows through radiator coils and air flows past the coils,

which cools the coolant and heats the incoming air. Due to the many variables involved, selecting optimal heat exchangers is challenging. Hand calculations are possible, but much iteration is typically needed. As such, heat exchangers are most often selected via computer programs, either by system designers, who are typically engineers, or by equipment vendors. To select an appropriate heat exchanger, the system designers (or equipment vendors) would firstly consider the design limitations for each heat exchanger type. Though cost is often the primary criterion, several other selection criteria are important, High/low pressure limits, Thermal performance, Temperature ranges, Product mix (liquid/liquid, particulates or high-solids liquid), Pressure drops across the exchanger, Fluid flow capacity, Clean ability, maintenance and repair, Materials required for construction, Ability and ease of future expansion Material selection, such as copper, aluminum, carbon steel, stainless steel, nickel alloys, ceramic, polymer, and titanium. Small-diameter coil technologies are becoming more popular in modern air conditioning and refrigeration systems because they have better rates of heat transfer than conventional sized condenser and evaporator coils with round copper tubes and aluminum or copper fin that have been the standard in the HVAC industry. Heat exchangers can be classified in a number of ways, depending on their construction or on how fluid move relative to each other through the device. There are various heat exchangers in which some heat exchangers are, Double pipe heat exchanger Shell and tube heat exchanger, Compact heat exchanger, Cross flow heat exchanger and Ceramics
The word “ceramic” came from Greek word it means a ceramic is an inorganic, nonmetal or metalloid atoms primarily held in ionic and covalent bonds pottery.

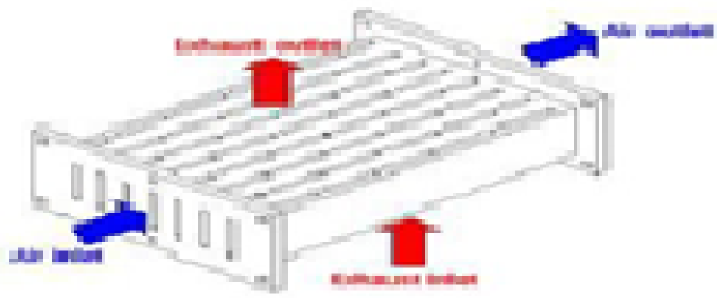

Fig 1schematic diagram of ceramic heat exchanger

Low temperature - Although ceramic heat exchangers lend themselves to medium and high temperature applications, they can be used in the 500°F to 1400°F range. If the flue gas is corrosive and/or abrasive, the machine is a practical piece of equipment to preheat combustion air for dryers and other similar processes.

Medium temperature - Most ceramic exchangers are designed for the 1400°F to 2200°F range, and Heat Transfer International has several full size exchangers operating successfully in these ranges.

High temperature - Special ceramics can be incorporated into the Heat Transfer International heat exchanger to take temperatures up to 2400°F

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In this study, the ceramic heat exchanger of 3 pass recuperate was analyzed to predict the performance, for example, heat transfer rate, effectiveness, and pressure drop, and so on since the ceramic heat exchanger has characteristics of cheap material cost, but low thermal efficiency compared to metallic heat exchangers.

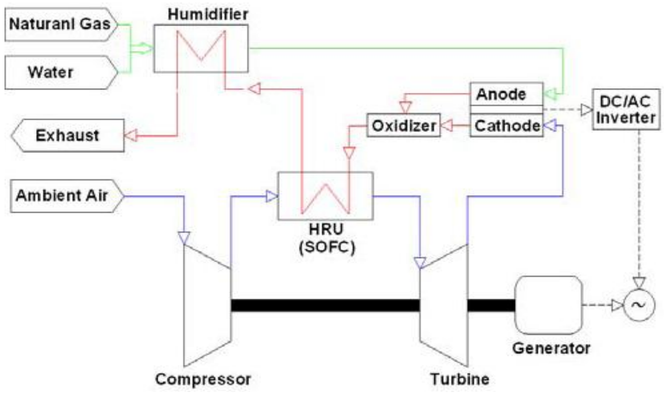


Fig 1.2shows working principle of heat exchanger.

## 1.1 OBJECTIVES OF PRESENT STUDY:

The present work include following objectives

1. Designing of Rectangular, circular and elliptical shapes using CREO-PARAMETRIC 3.0

2. Simulating the designs with ANSYS FLUENT 15.

3. To enhance heat transfer coefficient of Rectangular, circular and elliptical tubes.

4. Comparing heat transfer coefficient between optimized tubes.

## 1.2 MODELLING AND SIMULATION:

The heat exchanger is formed by taking a rectangular ceramic block of 315×202.5×241.5 mm. Ducts for the flows are cut Ducts for the flows are cut in rectangular, elliptical and cylindrical shapes as per the designed dimensions. The whole model is created in CREO 3.0.

## II.GOVERNING EQUATIONS OF FLUID FLOW:

2.1 Continuity Equation:

The equation based on the principle of conservation of mass is called continuity equation. The conservation of mass law applied to a fluid passing through an infinitesimal, fixed control volume yields the following equation of continuity,

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \qquad (2.1)$$

$$\frac{\partial \rho}{\partial t}+div(\rho V)=0 \qquad (2.2)$$

Where 'ρ' is the fluid density, u, v, and w is the fluid velocity vectors. For an incompressible flow, the density of each fluid element remains constant.

## 2.2OVERALL HEAT TRANSFER COEFFICIENT OF THE CERAMIC HEAT EXCHANGER:

### 2.2.1 $\xi$ -NTU METHOD:

The thermal performance of the ceramic heat exchanger was calculated by theoretical equation of $\xi$ NTU method for which the effectiveness (ξ) is expressed as Eq. (2.2.1) in unmixed fluid flow condition,
and then compared to that by the numerical computation.

$$\xi = 1 - \exp\left[\frac{NTU^{0.22}}{C}\left[\exp(-C\,NTU^{0.78}) - 1\right]\right]$$

Table 1. Correlations of Nusselt number in a duct from the literature:

| Reference | Correlation | Condition | | Range of validity |
|---|---|---|---|---|
| | | Geometry | Flow regime | |
| Kay and Crawford[2] | $Nu_{fd}=8.235(1-1.883/\alpha+3.767/\alpha^2-5.814/\alpha^3+5.361/\alpha^4-2/\alpha^5)$ | Rectangular | Fully developed | $Re<2200$ |
| Sieder-Tate[3] | $Nu=1.86(RePrD/L)^{1/3}(\frac{\mu_f}{\mu_w})^{0.14}$ | Circular | Simultaneously developing | $Re<2200$ |
| Stephan and preußer[4] | $Nu=4.364+\frac{0.086(RePrD/L)^{1.33}}{1+0.1Pr(ReD/L)^{0.83}}$ | Circular | Simultaneously developing (constant wall heat flux) | 0.7<Pr<7 or $RePrD/L<33$ (for Pr>7) |
| Shah and London[5] | $Nu=\begin{cases}1.953(RePr\frac{D}{L})^{1/3} & (RePr\frac{D}{L})\geq 33.3\\ 4.364+0.0722RePr\frac{D}{L} & (RePr\frac{D}{L})<33.3\end{cases}$ | Circular | Thermally developing laminar (constant wall heat flux) | - |

## III.THEORITICAL ANALYSIS OF HEAT EXCHANGER:

3.1Calculations:

**1) Total Flow Area:**

Air Side At = (W × H) × Number of Channels = 0.052 × 0.0065 × 7 = 0.002366 m2

Exhaust Side at = (W × H) × Number of Channels = 0.052 × 0.0065 × 8 = 0.02704 m2

**2) Hydraulic Diameter:** Dh = 4A/P = (4 × (0.052 × 0.0065))/(2 × (0.052 + 0.0065)) = 0.01156 m2

**3) Velocity:**

Air side Va = m/ρA = 0.001983/(0.391 × 0.002366) = 2.14358m/s

Exhaust Side Va = m/ρA = 0.001983/ (0.34 × 0.02704) = 0.1875 m/s

**4) Reynolds Number (Re.No.):**

Air Side, Re.No. = ρVD"h"/μ = (0.391 × 4.287 × "0.01156")/(39.925 × 10-6) = 585

Exhaust Side, Re.No. = ρVD"h"/μ = (0.34 × 0.863 × "0.01156")/(43.00 × 10-6) = 79

**5) Nusselt Number and Convective Heat Transfer Coefficient**:

Air Side,

**6) Kay's and Crawford Correlation:**

Nu = 8.235(1 – 1.883⁄α+3.767⁄(α"2" –5.814 ⁄ (α"3" + 5.361⁄(α"4" -2⁄α"5" ))))

Aspect Ratio, α = (0.052/0.0065) = 8

Nu = 8.235(1 – 1.883⁄8 + 3.767⁄(8"2"–5.814⁄ (8"3" + 5.361⁄(8"4"–2⁄8"5" ))))

Nu = 6.7

h"air" = Nu × k/D"h" = 6.7 × (0.062 × 0.01156) = 35.93w/m^r k

h"gas" = Nu × k/D"h" = 6.7 × (0.0701 × 0.01156) = 40.057 W/m2 K

**7) Sieder-Tate correlation**:

Nu = 1.86(RePrD"h"⁄L)"0.33" (μ"f"⁄μ"w")"0.14"

Nu = 1.86((585 × 0.7011 × 0.01156) ⁄ 0.335)"0.33" (0.00003875 ⁄ 0.00004305)"0.14"

Nu = 4.395

h"air" = Nu × k/D"h" = 4.394 × (0.06362 × 0.01156) = 23.56 W/m2 K

h"gas" = Nu × k/D"h" = 4.394 × (0.0701 × 0.01156) = 26.64 W/m2 K

**8) Stephan Correlation:**

Nu = 4.364 + 0.086(RePrD"h"⁄L)"1.33"/(1 + 0.1Pr (ReD"h"⁄L)"0.83")

Nu = 4.364 + 0.086((585 × 0.7011 × 0.01156) ⁄ 0.335)"1.33"/(1 + 0.1 × 0.7011((585 × 0.01156) ⁄ 0.335)"0.83" )

Nu = 5.942

h"Air" = Nu × k/D"h" = 5.942 × (0.06362 × 0.01156)=31.869

h"air" = Nu × k/D"h" = 5.942 × (0.06362 ×0.1156 ) = 35.98 W/m2 K

**9) Shah and London Correlation:**

Nu = 4.364 + 0.0722(RePrD"h" ⁄ L)

Nu = 4.364 + 0.0722((585 × 0.7011 × 0.01156) ⁄ 0.335)

Nu = 5.385

h”aIr” = Nu × k/D”h” = 5.385 × (0.06362 × 0.01156) = 28.86 W/m2 K

h”gas” = Nu × k/D”h” = 5.385 × (0.07012 × 0.01156) = 32.6 W/m2 K

**10) Overall Heat Transfer Coefficient:**

U = 1/(1/h”air” + ΔX/k + A”air”/(η”t”A”gas”h”gas”)) = 1/(1/35.93 + 0.0065/77.5 + 0.03675/(0.75 × 0.07922 × 40.57))

U = 23.145W/m”2” K

**11) Effectiveness (NTU- Method):**

NTU = (UA⁄C”min”) = ((23.145 × 0.03675)/4.441) = 0.87118

C = Cmin/Cmax = 2.2040/2.2580 = 0.9763

ε = 1-exp {NTU”0.22”/C [exp(–CNTU”0.78” )–1]} × 100%

ε = 1–exp {0.87118»0.22»/0.984 [exp (–0.984 × 0.87118”0.78”) – 1]} × 100%

ε = 38.5%

**12) Total Heat Transfer Rate:**

q = ε × C»min» (T»gas_in»-T”air_in”) =0.38*2.20450(850-560)=247.677W

For elliptical:

**13) Calculation of C for cold fluid:**

C= Mass flow rate * specific heat

C=mc

=0.001983*1111.7

C= 2.20450W/K.

**14) Calculation of C for hot fluid:**

C= Mass flow rate * specific heat

C=mc=0.001983*1138.7

C=2.2580W/K

From this Cmin= 2.20450 and Cmax= 2.2580

C= Cmin/Cmax= 2.20450/2.2580

C=0.9763

**15) Surface area of a rectangle (A)** :

A = 2(L*W+L*H+W*H)

2(315\1000*6.5/1000+315/1000*52/1000+6.5/1000*52/1000)

A = 0.03675m2

**16) Surface area of circular**

A = $2\pi r2$ +$2\pi$rh

=2*$\pi$*(3.25/1000)2+2* $\pi *$ 3.25/1000*315/1000

A=6.49*10-3m26)

**17)Overall Heat Transfer Coefficient:**

U = 1/(1/h”air” + ΔX/k + A”air”/(η”t”A”gas”h”gas”)) = 1/(1/35.93 + 0.0065/77.5 +6.49*10^(-3)/(0.75 × 0.07922 × 40.57))=32.67W/m”2” K

**18) Effectiveness (NTU- Method)**:

NTU = (UA⁄C”min”) = ((32.67 × 6.49*10^(-3))/2.20450) = 0.096

ε = 1-exp {NTU”0.22”/C [exp(–CNTU”0.78” )–1]} × 100%

ε = 1–exp {0.096»0.22»/0.9763 [exp (–0.9763 × 0.096”0.78”) – 1]} × 100%

ε = 69.9%

**19) Total Heat Transfer Rate**:

q = ε × C»min» (T»gas_in»-T”air_in”) =0.699*2.20450(850-560)=446.874W

Surface area of elliptical

A = $\pi$ab

=$\pi$*0.315*6.5=6.43*10^(-3)m2.

**20) Overall Heat Transfer Coefficient:**

U = 1/(1/h”air” + ΔX/k + A”air”/(η”t”A”gas”h”gas”)) = 1/(1/35.93 + 0.0065/77.5 +6.43*10^(-3)/(0.75 × 0.07922 × 40.57))=32.64W/m”2” K

7) Effectiveness (NTU- Method):

NTU = (UA⁄C”min”) = ((32.64 × 6.49*10^(-3))/2.20450) = 0.096

ε = 1-exp {NTU”0.22”/C [exp(–CNTU”0.78” )–1]} × 100%

ε = 1–exp {0.096»0.22»/0.9763 [exp (–0.9763 × 0.096”0.78”) – 1]} × 100%

ε = 68.9%

**21) Total Heat Transfer Rate:**

q = ε × C»min» (T»gas_in»-T”air_in”) =0.68*2.20450(850-560) =434.7

## IV. NUMERICAL ANALYSIS OF HEAT EXCHANGER:

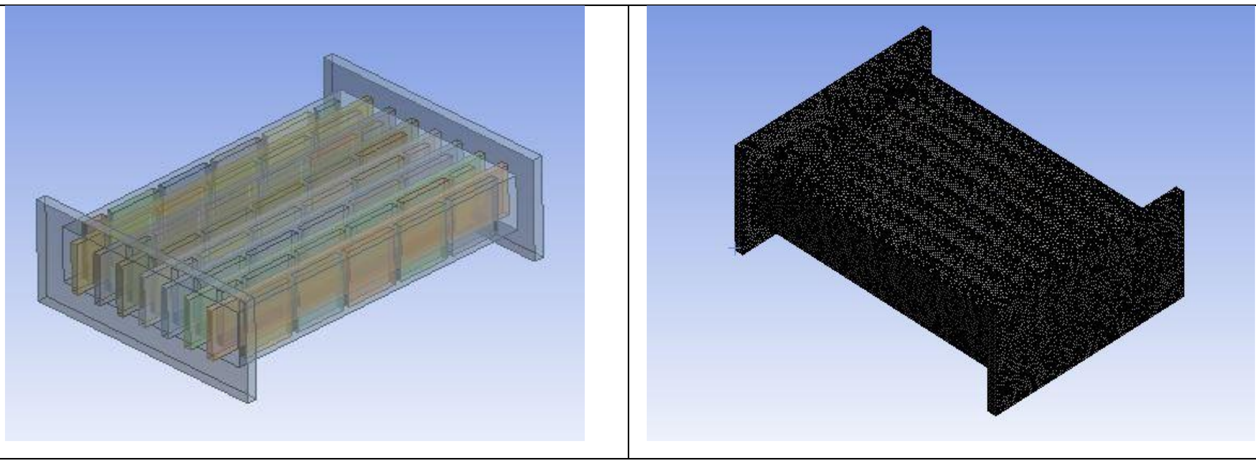

**FIG 4.1 graphical representations and meshing of rectangular tube.**

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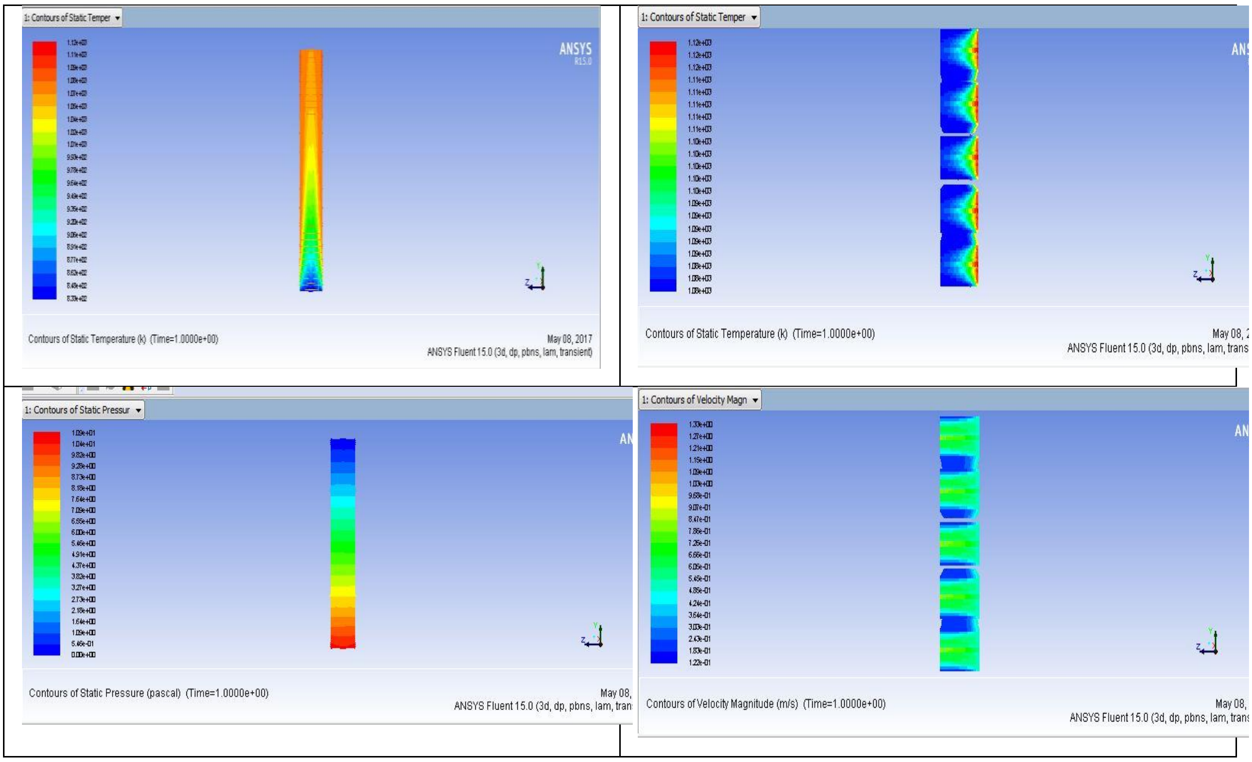


**Fig 4.2 Shows Contours Of pressure, velocity and temperature of rectangular tube heat exchanger:**

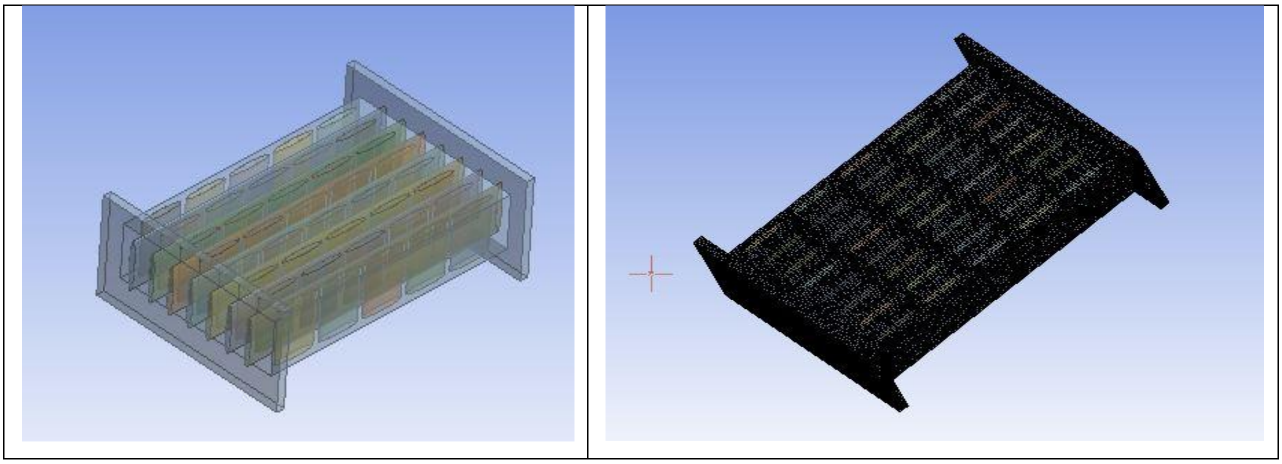

**Fig 4.3 shows geometrical representation and meshing model of elliptical tube**

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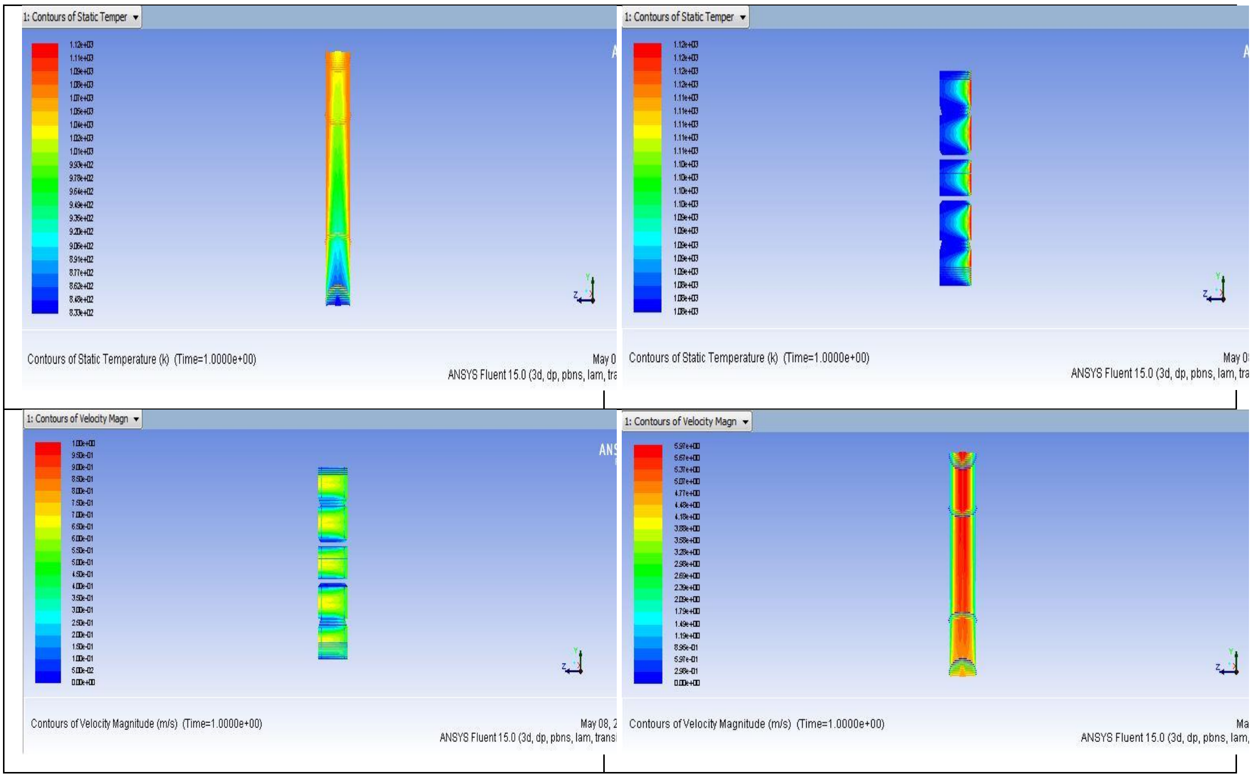


**Fig.4.4 shows contours of pressure, velocity and temperature of elliptical tube heat exchanger at air side and exhaust side**

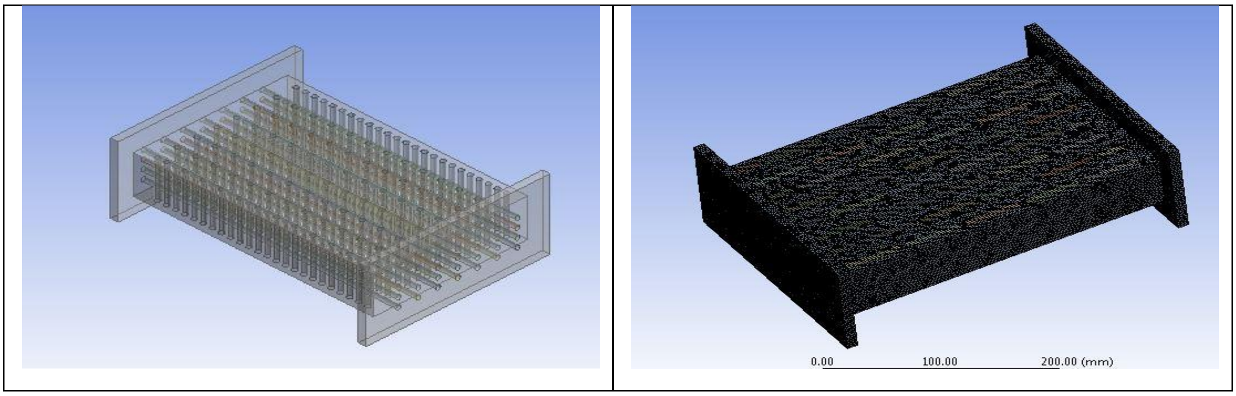


**Fig 4.5 shows geometrical representation and meshing model of cylindrical tube:**

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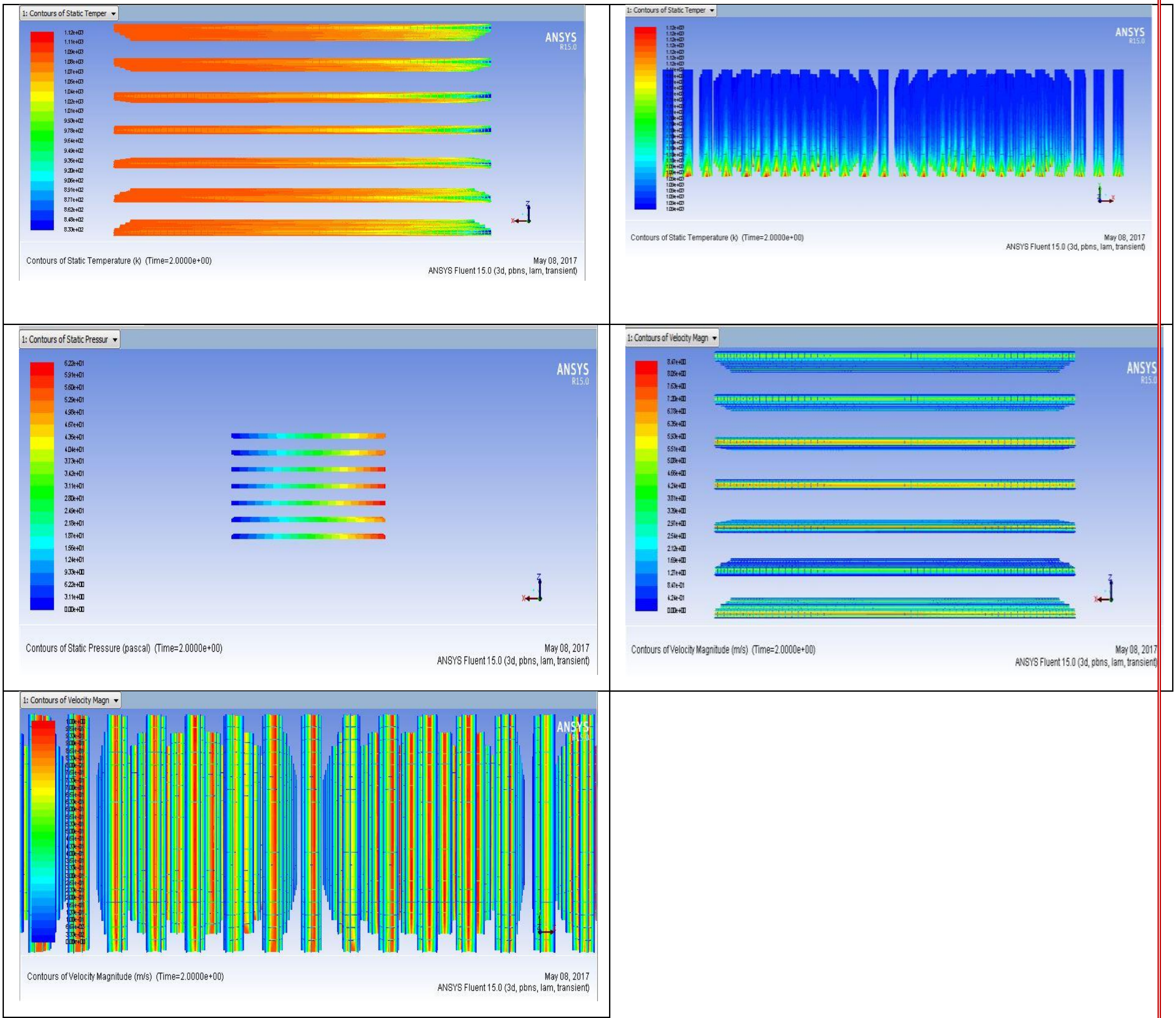


**Fig 4.6shows contours of pressure, velocity and temperature of cylindrical tube heat exchanger at air side and exhaust side:**

## V.RESULTS AND DISCUSSION

Table 5.1 Comparison between Reynolds Number & Correlations:

| Reynolds No | | 585 | 736 | 888 | 1040 | 1192 |
|---|---|---|---|---|---|---|
| Rectangle | Pressure | 0.0198 | 0.0169 | 0.00921 | 0.00650 | 0.00234 |
| | Velocity | 6.231 | 4.934 | 2.421 | 1.0747 | 0.0543 |
| | Temperature | 835.2 | 834.5 | 833.12 | 832.97 | 831.59 |
| Elliptical | Pressure | 0.018064 | 0.01690078 | 0.01323807 | 0.006509 | 0.00356 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Velocity | 0.61700254 | 0.77143 | 0.92246 | 1.0747096 | 1.098563 |
| | Temperature | 833.34 | 833.15 | 833.03 | 832.97 | 832.56 |
| Cylinder | Pressure | 0.227896 | 0.249018 | 0.262542 | 0.293062 | 0.318870 |
| | Velocity | 0.098198 | 0.196825 | 1.17370 | 1.355605 | 1.5821868 |
| | temperature | 832.34 | 831.01 | 830.12 | 829.46 | 829.16 |

Table 5.2 Comparison between Mass flow rate & Correlations:

| Mass flow rate | 0.001983 | 0.002479 | 0.002975 | 0.00347 | 0.003966 |
|---|---|---|---|---|---|
| Reynolds no | 585 | 736 | 888 | 1040 | 1192 |
| Rectangle | 525 | 636.29 | 736.9 | 828.86 | 912.137 |
| Elliptical | 529 | 640 | 740.2 | 832.7 | 916 |
| cylindrical | 558 | 669.9 | 783.3 | 887.75 | 983.6 |

Table 5.4 Effectiveness between rectangle, elliptical and cylindrical shapes from numerical analysis:

| Comparison between theoretical and numerical effectiveness | | | | | | |
|---|---|---|---|---|---|---|
| Reynolds no | | 585 | 736 | 888 | 1040 | 1192 |
| Effectiveness(Theoretical) | Elliptical | 0.41 | 0.42 | 0.43 | 0.45 | 0.46 |
| | Cylindrical | 0.54 | 0.56 | 0.57 | 0.59 | 0.6 |
| | Rectangle | 0.53 | 0.54 | 0.55 | 0.57 | 0.58 |
| Effectiveness(Numerical) | Elliptical | 0.56 | 0.56 | 0.57 | 0.6 | 0.61 |
| | Cylindrical | 0.69 | 0.71 | 0.72 | 0.74 | 0.75 |

Table 5.5Effectiveness based on Shah & London relation:

| Based on Shah &London correlations | | | | | | |
|---|---|---|---|---|---|---|
| Reynolds no | | 585 | 736 | 888 | 1040 | 1192 |
| | U | 20.57 | 20.96 | 21.73 | 21.87 | 22.71 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Rectangle | Є | 0.37 | 0.38 | 0.39 | 0.41 | 0.42 |
| | Q(W) | 532.08 | 606.54 | 693.45 | 717.34 | 737.66 |
| Elliptical | U | 27.2 | 27.2 | 27.2 | 27.2 | 27.2 |
| | Є | 0.4 | 0.41 | 0.42 | 0.44 | 0.45 |
| | Q(W) | 608.1 | 619.3 | 630.4 | 642.3 | 667.5 |
| Cylindrical | U | 29.62 | 29.62 | 29.62 | 29.62 | 29.62 |
| | Є | 0.52 | 0.54 | 0.55 | 0.57 | 0.59 |
| | Q(W) | 745.6 | 756.8 | 772.1 | 801.4 | 843.1 |

Table 5.6 Effectiveness based on Sieder-Tate relation:

| Based on Sieder-Tate correlations | | | | | | |
|---|---|---|---|---|---|---|
| Reynolds no | | 585 | 736 | 888 | 1040 | 1192 |
| | U | 15.214 | 16 | 16.5 | 17.01 | 17.406 |
| Rectangle | Є | 0.36 | 0.37 | 0.39 | 0.4 | 0.41 |
| | Q(W) | 360 | 405.5 | 436.54 | 460.1 | 479.66 |
| Elliptical | U | 21.12 | 22.8 | 23.1 | 24.2 | 25.8 |
| | Є | 0.38 | 0.39 | 0.4 | 0.41 | 0.42 |
| | Q(W) | 515 | 532 | 545.8 | 556.7 | 571 |
| Cylindrical | U | 24.12 | 25.3 | 25.62 | 27.01 | 27.56 |
| | Є | 0.5 | 0.51 | 0.52 | 0.54 | 0.56 |
| | Q(W) | 422.65 | 444.3 | 456.3 | 474.8 | 498.9 |

Table 5.7 Effectiveness based on Kay's and Crawford relation:

| Based on Kay's & Crawford Nusselt no correlations | | | | | | |
|---|---|---|---|---|---|---|
| Reynolds no | | 585 | 736 | 888 | 1040 | 1192 |
| | U | 23.145 | 23.145 | 23.04 | 23.14 | 23.14 |
| Rectangle | Є | 0.38 | 0.39 | 0.4 | 0.42 | 0.43 |
| | Q(W) | 247.67 | 262.8 | 288.2 | 296.1 | 305.2 |
| Elliptical | U | 27.3 | 27.3 | 27.3 | 27.3 | 27.3 |
| | Є | 0.41 | 0.42 | 0.43 | 0.45 | 0.46 |
| | Q(W) | 315.23 | 333.47 | 356.28 | 378.12 | 392.11 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| Cylindrical | U | 32.64 | 32.64 | 32.64 | 32.64 | 32.64 |
| | € | 0.54 | 0.56 | 0.57 | 0.59 | 0.62 |
| | Q(W) | 446.87 | 468.21 | 485.3 | 506.89 | 516.13 |

5.2.1 Graphical representation:

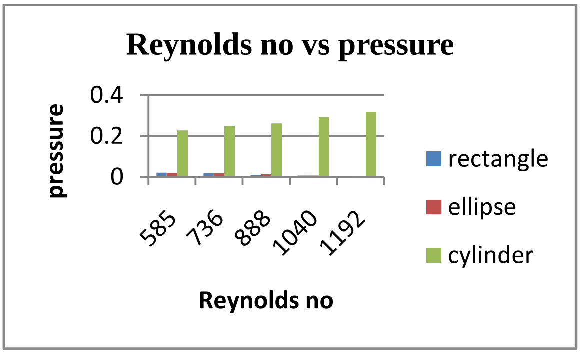


Fig.5.2.2 shows the variation of Reynolds no with pressure between rectangle, elliptical and cylindrical tubes.

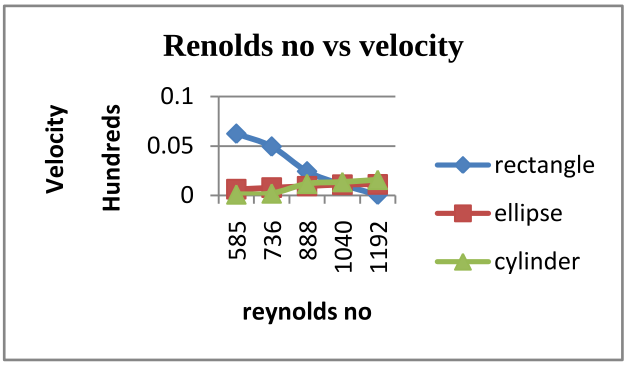


Fig.5.2.3 shows the variation of Reynolds no with velocity between tubes.

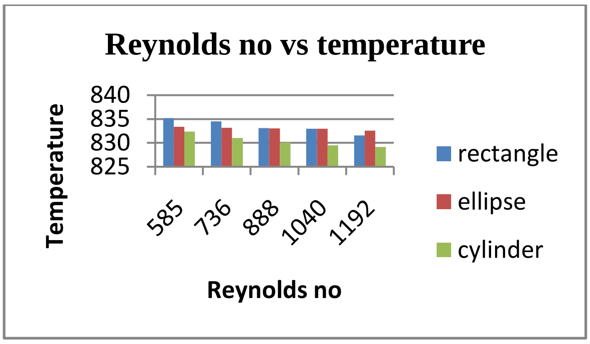


Fig.5.2.4 shows the variation of Reynolds no with temperature between rectangle, elliptical and cylindrical tubes.

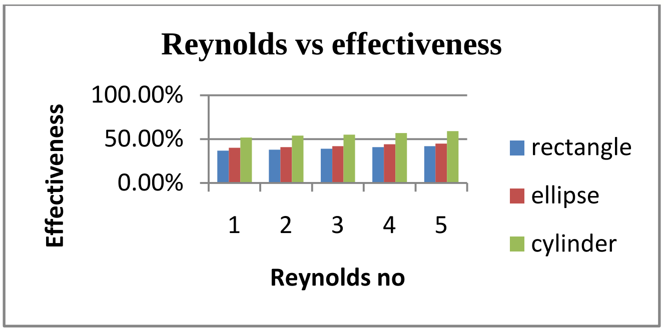


Fig.5.2.5 shows the variation of Reynolds no with effectiveness between rectangle, elliptical and cylindrical tubes.

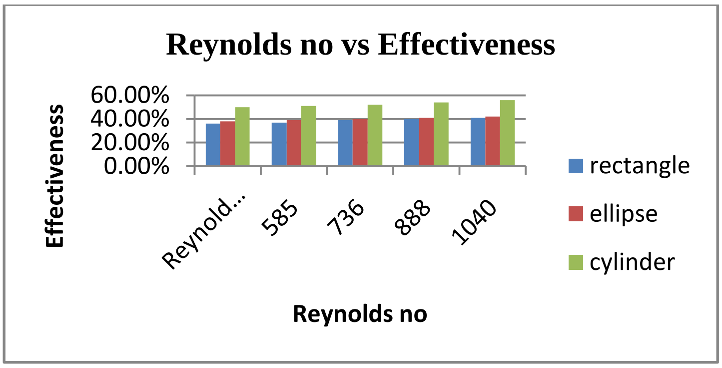


Fig.5.2.6 shows the variation of Reynolds no with effectiveness

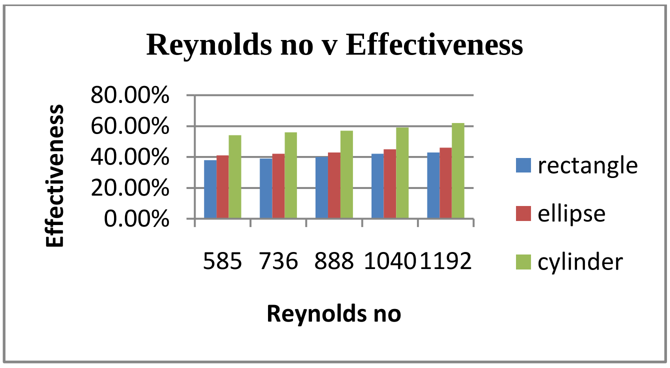


Fig.5.2.7shows the variation of Reynolds no with effectiveness

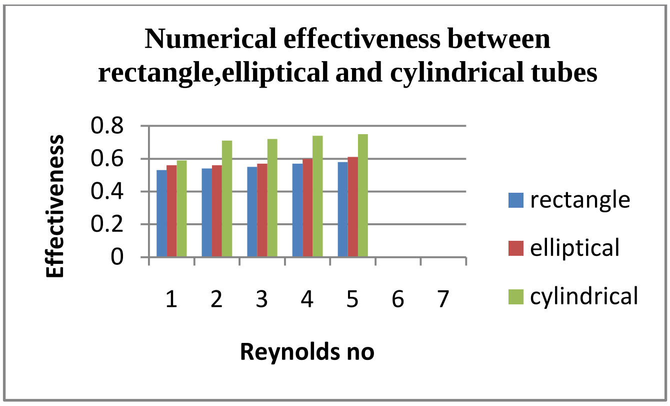


FIG.5.2.8Numerical effectiveness between rectangular, elliptical and cylindrical tubes**:**

## VI. CONCLUSION

In current research the ceramic monolith heat exchanger performance was performed in theoretical and numerical analysis. The theoretical calculations have been executed for the exhaust gas as well as cold air for a measuring domain of 600-1000c. The total heat transfer rate and effectiveness were estimated for theoretical and numerical analysis. The calculations have been executed utilizing NTU method considering numerous Nusselt number correlations taken from the literature.

(1) The performance of the heat transfer of cylindrical tube is more than elliptical and rectangular tube .Among the tubes the estimated Effectiveness for rectangular tube heat exchanger, elliptical tube heat exchanger and cylindrical tube heat exchanger are 40%, 43% and 52% respectively in numerical analysis.

**(**2) The estimated Effectiveness for rectangular tube heat exchanger, elliptical tube heat exchanger and cylindrical tube heat exchanger are 52%, 55% and 62% respectively in numerical analysis.

## VII.FUTURE SCOPE

In this project the entire work is carried out using ceramic materials of Ni-Cr-Al, NiCrAl + $MgZrO_3$ and $MgZrO_3$. In the same manner it can be carried out by make use of advanced ceramic materials those are high temperature resistant in nature.

Apart from the regular cross sections like Rectangular, Elliptical and Cylindrical, other cross sections can be used by maintaining proper L/D ratio and without varying any mass distribution.

Also instead of simply releasing smoke stack exhaust, it can be used to heat air in the pre heater enabling the pre heater to operate at a lower, energy saving temperature, provided the parameters for a particular application have been established.

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