Computational Analysis of Heat Transfer in Heat Exchanger Using Cfd

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Abstract*- Metal heat exchangers are proven devices in many industrial applications, but process and technology advances have pushed metal heat exchangers beyond their performance limits. The costly materials required for higher temperature and the frequently corrosive operating environments drive up overall costs and compromise system durability.Three different heat exchangers with different material have been learnt for finding out heat transfer performance and effectiveness on computing numerically and ξ-NTU method. In entire domain computation numerically has been performed along with fluid region in rectangular ducts of exhaust gas side, ceramic core and rectangular duct fluid region in air side with the air exhaust in direction of cross flow. In addition, the heat exchanger was also analyzed to estimate the performance by conventional ξ -NTU method with Nusselt number correlation for flow in rectangular duct. Effectiveness of heat exchangers has been found by ξ-NTU method and LMTD method. The three different heat exchangers are compared in terms of effectiveness, pressure drop, dynamic pressure, static temperatures and total temperatures.*

Keywords- high temperature heat exchangers, effectiveness, pressure drop, CFD analysis.

I. INTRODUCTION

Using passive techniques in order to enhance heat transfer characteristics in heat exchanger has been an interesting topic for scientists and researchers during recent decades. Numerical and experimental studies have been conducted in order to improve heat transferred by these techniques. The demand of reduction of the cost and dimensions of heat exchanger has motivated the searchers to investigate different ways of heat transfer enhancement. Passive heat transfer enhancement techniques are mostly preferred due to their simplicity and applicability in many applications.

II. LITERATURE REVIEW

Paeng JG, Yoon YH, Kim KH, Yoon KS. (1) stated that heat resistant material is required in constructing high temperature heat exchangers. They judged the ceramic monolith heat exchanger performance, calculating pressure drop and heat transfer by numerical computation and the ε-NTU technique.

Nagarajan V, Chen Y, Wang Q, (2) predicted that the thermal–hydraulic performances of compact surface heat exchangers are strongly influenced by their geometry and flow configurations. A novel fin configuration for high temperature ceramic Plate-Fin Heat Exchanger (PFHE) was brought up utilizing the three-dimensional Computational Fluid Dynamics (CFD) FLUENT code.

Zeng M, Ma T, Sunden B, Trabia M B (3)numerically investigated the lateral fin profiles effect on stress functionality of finned tubes internally in a greater temperature heat exchanger using ANSYS software. Three types of lateral fin profiles, specifically S-shape, Z-shape and V-shape have been learnt and assessed.

De Mello PEB, Monteiro DB (4) stated ceramic materials are the preferable natural alternative for the High Temperature Heat Exchanger (HTHE). Current research contributed one thermodynamic research of one EFGT (Externally Fired Gas Turbine) with one briefed model for the ceramic heat exchanger.

Monteiro DB, de Mello PEB (5) stated that there exists a possible requirement for heat exchangers competent of sustaining elevated temperatures, classically greater than 800°C, for utilization in thermal power plants. In implementing EFGT (Externally Fired Gas Turbines) cycles, these heat exchangers are utilized. Data for finned heat exchangers flat tubes.

III. MATHEMATICAL CALCULATION OF HEAT EXCHANGER

Demand of world energy consumption is steadily growing due to development of industries and increase of population. However, fossil fuels most available at this time will be exhausted in near future. Moreover, the fossil fuels cause environmental pollution and global warming. Therefore, fuel cell systems become interested in energy market for alternative energy sources.

SOFC- solid oxide fuel cell of various fuel cell types has more than 60% of electric conversion efficiency, but produces high exhaust gas temperature of $600{\sim}1000^0$. Therefore, a recuperator is need to recover the high temperature heat. Accordingly, heat resistance material is necessary for the high temperature heat exchanger. The recovered heat may be used to generate electricity utilizing a gas turbine as SOFC/GT hybrid power generating system as shown Fig. 1. Recently, a hybrid recuperator is interested for the power system. The hybrid recuperator consists of 3 pass recuperator, the first one is ceramic heat exchanger of which working temperature is from 600^0 to $1{,}000^0$, and the second and the third ones are metallic heat exchanger of which working temperature is under 600^0 as shown in Fig. 2. working temperatures of most conventional heat exchangers are generally less than 150^0.

In this study, the ceramic heat exchanger of 3 pass recuperator 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.

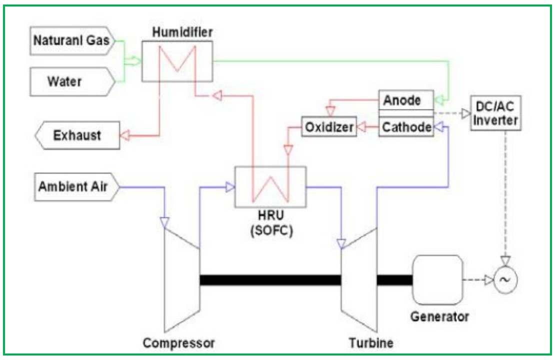

Fig 1: Schematic of SOFC/GT hybrid power generating system.

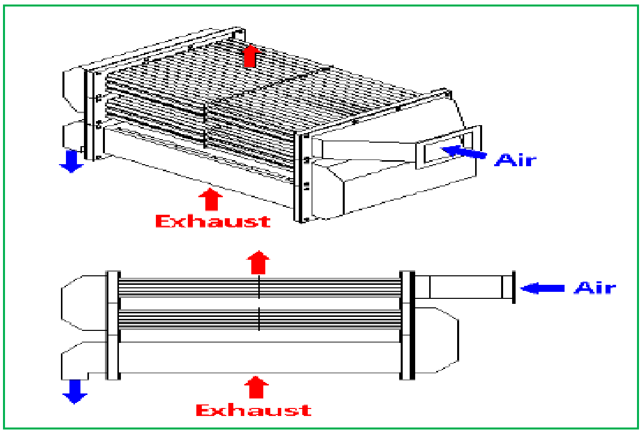

Fig 2: Schematic drawing of SOFC/GT hybrid recuperator.

Design And Analysis Model Of The Ceramic Recuperator

The ceramic recuperator consists of rectangular hot exhaust and cold air passages with the exhaust and air in cross flow direction without mixing each other as shown in Fig. 3.

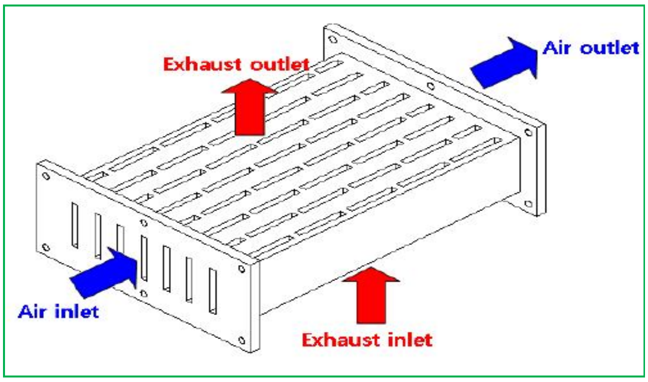

Fig 3: Schematic drawing of the ceramic heat exchanger.

Specification of model

1. Length of the ceramic heat exchanger: 315 mm.
2. Width of the ceramic heat exchanger: 65 mm.
3. Height of the slot 52 mm.
4. Width of slot 6.5 mm.
5. Breadth of the ceramic heat exchanger 52 mm.
6. Density of the ceramic material 3100 kg /m3.
7. Specific heat of the ceramic material 670 J / kgK.
8. Thermal conductivity of the ceramic material 77.5 W/mK.

Overall heat transfer coefficient of the ceramic heat exchanger

The overall heat transfer coefficient, *U*, between hot and cold fluids is a principal factor in estimating the rate of heat transfer. It is expressed as Eq. (1).

$$U = \frac{1}{\frac{1}{h_{air}} + \frac{\Delta X}{k} + \frac{A_{air}}{\eta_t A_{gas} h_{gas}}} \quad (1)$$

Here k is thermal conductivity of the ceramic core, ∆X is the thickness of the wall, and Aair and Agas are the air-side and the exhaust-side heat transfer areas, and h_{air} and h_{gas} are also each side average convective heat transfer coefficients, which are obtained from Nusselt relation of Eq. (2). In addition, η is the total surface effectiveness of a fin.

$$h = Nu \times \frac{k}{D_h} \quad (2)$$

K of above equation is thermal conductivity of each fluid and *Dh* is a hydraulic diameter of the rectangular fluid passage.

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Table 1. Correlations of Nusselt numbers in ducts as reported in the literature.

Reference	Correlation	Conditions		Range of validity
		Geometry	Flow regime	
Kays and Crawford [9]	$Nu=8.235(1-1.883/\alpha+3.767/\alpha^2-5.814/\alpha^3+5.361/\alpha^4-2/\alpha^5$	Retangular	Fully developed (constant Wall heat flux)	$Re<2200$
Sieder-Tate correlation [10]	$Nu=1.86(RePrD_h/L)^{1/3}\left(\frac{\mu_f}{\mu_w}\right)^{0.14}$	Circular	Simultaneously developing (constant wall temperature)	$Re<2200$
Stephan correlation [11]	$Nu=4.364+\frac{0.086(RePrD_h/L)^{1.33}}{1+0.1Pr(ReD_h/L)^{0.83}}$	Circular	Simultaneously developing Simultaneously developing (constant wall temperature)	$0.7<Pr<7$ or $RePrD/L<33$ (for $Pr>7$)
Shah and London [12]	$Nu=\begin{cases}1.953(RePrD_h/L)^{1/3}\\4.364+0.0722(RePrD_h/L)\end{cases}$	Circular	Thermally developing laminar (constant wall temperature)	$RePrD/L\geq33$ $RePrD/L<33$

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

$$\xi = 1-\exp\,[NTU^{0.22}/C[\exp(-CNTU^{0.78})-1]]$$

Here, C is the ratio of heat capacity (*C*min/*C*max).

NTU is defined by the total conductance (UA) divided by minimum heat capacity(C_{min}), where C_{min} is the lower heat capacity and C_{max} is the higher heat capacity ($C = m \times c_p$) of the two fluids with *m* and c_p are mass flow rate and specific heat of the hot and cold fluids, respectively.
Then rate of heat transfer

$$q=\xi \times C_{min}[T_{gasin}-T_{airin}]$$

Outlet temperatures of exhaust and air are evaluated with inlet temperatures of both fluids as Eq

$$T_{airout}= T_{airin}+(q/C_{pair})$$
$$T_{gasout}= T_{gasin}+(q/C_{pgas})$$

Pressure Drop

Pressure drop is a major factor for the rating of the heat exchanger with the heat transfer rate. The Darcy friction equation is provided for the pressure drop in Eq.

$$\Delta P = f\,\frac{1}{2}\,\rho_m\,v_m^2\,\frac{L}{D}$$

Where f = 64/Re.

Calculation

Total Flow Area

Air Side At = (W × H) × Number of Channels
= 0.052 × 0.0065 × 7 = 0.002366 m^2
Exhaust Side at = (W × H) × Number of Channels
= 0.052 × 0.0065 × 40 = 0.01352 m^2

Hydraulic Diameter,

Dh = 4A/P = (4 × (0.052 × 0.0065))/(2 × (0.052 + 0.0065)= 0.01156 m^2

Velocity

Air side Va = m/ρA = 0.003966/(0.391 × 0.002366) = 4.287 m/s
Exhaust Side Va = m/ρA = 0.003966/ (0.34 × 0.01352) = 0.863 m/s

Reynolds Number (Re.No.)

Air Side, Re.No. = $\rho V D_h/\mu$
= (0.391 × 4.287 × ”0.01156”)/(39.925 × 10-6) = 485.16
Exhaust Side, Re.No. = $\rho V D_h/\mu$
= (0.34 × 0.863 × ”0.01156”)/(43.00 × 10-6) = 78.83

Nusselt Number and Convective Heat Transfer Coefficient:

Air Side,
Kays and Crawford Correlation,
Nu = 8.235[1 –(1.883⁄α)+(3.767⁄α^2) –(5.814 ⁄ $\alpha^{3)}$ + (5.361⁄α^4)-(2⁄α^5)]
Aspect Ratio, α = (0.052/0.0065) = 8

$Nu = 8.235[1 - (1.883/8) + (3.767/8^2) - (5.814/8^{3)} + (5.361/8^4) - (2/8^5)]$

$= 6.7$

$h\text{"air"} = (Nu \times k)/D_h = (6.7 \times 0.06362) / 0.01156 = 36.863\ W/m^2\ K$

Exhaust side,

Kays and Crawford Correlation,

$Nu = 8.235[1 - (1.883/\alpha) + (3.767/\alpha^2) - (5.814/\alpha^{3)} + (5.361/\alpha^4) - (2/\alpha^5)]$

Aspect Ratio, $\alpha = (0.052/0.0065) = 8$

$Nu = 8.235[1 - (1.883/8) + (3.767/8^2) - (5.814/8^{3)} + (5.361/8^4) - (2/8^5)]$

$= 6.7$

$h\text{"air"} = (Nu \times k)/D_h = (6.7 \times 0.06362) / 0.01156 = 40.56\ W/m^2\ K$

Overall Heat Transfer Coefficient:

$U = 1/[(1/h_{air)} + (\Delta X/k) + (A_{air} / (\eta_t A_{gas} h_{gas}))]$

$= 1/[(1/36.863) + (0.0065/77.5) + (0.257/(0.75 \times 0.1352 \times 40.56))]$

$= 11.15\ W/m^2\ K.$

Outlet temperature calculations for different mass flow rates

(i)Outlet temp calculations at m_{air} =0.001983 Kg/sec

Air in = 904 Exhaust in = 1060

$m_{air}=0.001983$ $m_{gas}=0.001983$

$C_{air} = m \times Cp_{air}$

$= 0.001983 \times 1111.7 = 2.2011$

$C_{gas} = m \times Cp_{gas}$

$= 0.001983 \times 1138.7 = 2.2546$

$C = C_{min}/C_{max} = C_{air} / C_{gas}$

$= 2.2011/2.254 = 0.9762$

$NTU = UA/ C_{min}$

$= (11.15 \times 0.1892)/2.2011$

$= 0.958$

$\xi = 1\text{-exp}\ [NTU^{0.22}/C[\exp(-CNTU^{0.78})-1]]$

$= 1-e[(.958)^{0.22}/0.976[e(-(0.976)(0.958)^{0.78})-1]]$

$= 1-e[1.052(-0.648)]$

$= 0.46$

$q = \xi \times C_{min}[T_{gasin} - T_{airin}]$

$= 0.46 \times 2.2011\ [1060-904] = 158.63$

$T_{airout} = T_{airin} + (q/C_{pair})$

$= 904 + 158.63/2.2011 = 976$

$T_{gasout} = T_{gasin} + (q/C_{pgas})$

$= 1060 + 158.63/2.254 = 990$

S. NO	M_{air}	C	NTU	ε	q	T1	T2	T3	T4
1	0.001983	0.9762	0.958	0.46	158.63	904	1060	976	990
2	0.002479	0.8142	0.935	0.479	168.12	904	1060	964.7	985.4
3	0.002975	0.67	0.935	0.498	175.15	904	1060	956.9	982
4	0.003471	0.586	0.935	0.511	180	904	1060	950.6	980.2
5	0.003966	0.511	0.935	0.523	183.9	904	1060	945.7	978.4

Table1: ceramic heat exchanger theoretical results.

Initially, CATIA name is an abbreviation for Computer Aided Three-dimensional Interactive Application the French Dassault Systems .Before using sketch select the plane of the CATIA display and then go to sketch. So that generating of face can be done in CATIA. Draw the drawing which is having an accurate dimension then convert to three dimensional solid.

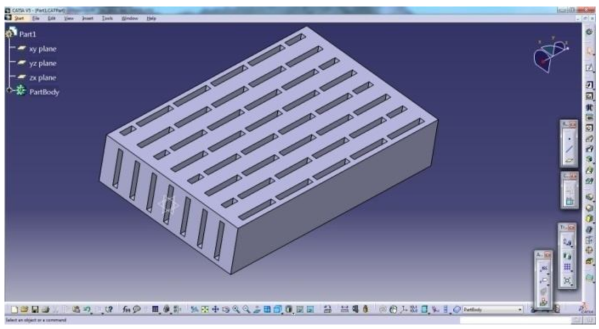


Fig4: final heat exchanger model created in catia

To run the Analysis, 64 bit operating system, 4GB ram And ANSYS 16.0 is used. Without any problem, to run analysis software this configuration is very apt. The previously created IGS file is imported on ANSYS file geometry. In ANSYS, static structure analysis is performed. The table which is shown below, different materials for different components are used bicycle seat assembly. Solid mesh 200 element are used to divide the geometric body in to small strips (Finite elements)

Computational fluid dynamics (CFD) study of the system starts with the construction of desired geometry and mesh for modeling the dominion. Generally, geometry is simplified for the CFD studies. Meshing is the discretization of the domain into small volumes where the equations are solved by the help of iterative methods. Modeling starts with the describing of the boundary and initial conditions for the dominion and leads to modeling of the entire system. Finally, it is followed by the analysis of the results, conclusions and discussions.

Heat exchanger is built in the ANSYS workbench design module. It is a counter-flow heat exchanger. First, the fluid flow (fluent) module from the workbench is selected. The design modeler opens as a new window as the geometry is double clicked. After import the model into ANSYS from CATIA, it will show the model as 3 parts . For merge operation, all the 4 parts are selected using control and merged as 1 part. At the end it will show as 1 part and 4 bodies. The 4 bodies within 1 part are named as follows:

Part number	Part name	State of part
1	exchanger	solid
2	Inlet air	fluid
3	Exhaust air	fluid

Table2 : Naming of various parts of the body with state type

Save the project at this point and close the window. Refresh and update the project on the workbench. Initially a relatively coarser mesh is generated. This mesh contains mixed cells (Tetra and Hexahedral cells) having both triangular and quadrilateral faces at the boundaries. Care is taken to use structured hexahedral cells as much as possible. It is meant to reduce numerical diffusion as much as possible by structuring the mesh in a well manner, particularly near the wall region. Later on, a fine mesh is generated. For this fine mesh, the edges and regions of high temperature and pressure gradients are finely meshed.

The mesh details view gave us the following information: Relevance centre: fine meshing ,Smoothing: high ,Size: 0.2 mm ,Nodes: 52003 and Elements: 52102

The different surfaces of the solid are named as per required inlets and outlets for inner and outer fluids. The outer wall is named as insulation surface. Save project again at this point and close the window. Refresh and update project on the workbench. Now open the setup. The ANSYS Fluent Launcher will open in a window. Set dimension as 3D, option as Double Precision, processing as Serial type and hit OK. The Fluent window will open. The mesh is checked and quality is obtained. The analysis type is changed to Pressure Based type. The velocity formulation is changed to absolute and time to steady state. Gravity is defined as y = -9.81 m/s2 .Energy is set to ON position. Viscous model is selected as “k-ε model (2 equation). Radiation model is changed to Discrete Ordinates. The create/edit option is clicked to add water-liquid and copper to the list of fluid and solid respectively from the fluent database.

S.NO	Properties	Ceramic core
1	Density(ρ)(Kg/m^3)	3100
2	Thermal conductivity(K)(W/mk)	77.5
3	(C_p)(J/Kg k)	670

Table3: Thermodynamic Properties Of Ceramic Core

S.NO	Properties	Steel core
1	Density(ρ)(Kg/m^3)	8030
2	Thermal conductivity(K)(W/mk)	16.27
3	(C_p)(J/Kg k)	502.4

Table4: Thermodynamic Properties Of Stainless Steel

S.NO	Properties	Steel core
1	Density(ρ)(Kg/m^3)	8190
2	Thermal conductivity(K)(W/mk)	11.2
3	(C_p)(J/Kg k)	435

Table5: Thermodynamic Properties Of Ni Allloy 718

The parts are assigned as water and copper as per fluid/solid parts.Boundary conditions are used according to the need of the model. The inlet and outlet conditions are defined as velocity inlet and pressure outlet. As this is a counter-flow with two tubes so there are two inlets and two outlets. The walls are separately specified with respective boundary conditions. No slip condition is considered for each wall. Except the tube walls each wall is set to zero heat flux condition.

Exhaust inlet temp = 1060 K, air inlet temp = 904 k, Mass flow rate in Tube m_h= 0.0019 kg/sec and Mass flow rate in Shell m_c= 0.0019 kg/sec

The number of iteration is set to 500 and the solution is calculated and various contours, vectors and plots are obtained.

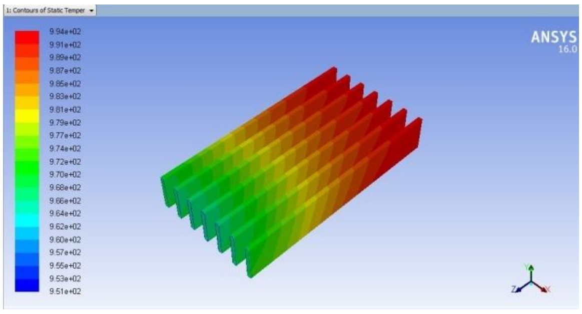


Fig5: Temperature distribution of ceramic core HE at mass flow rate of 0.001983kg/m3

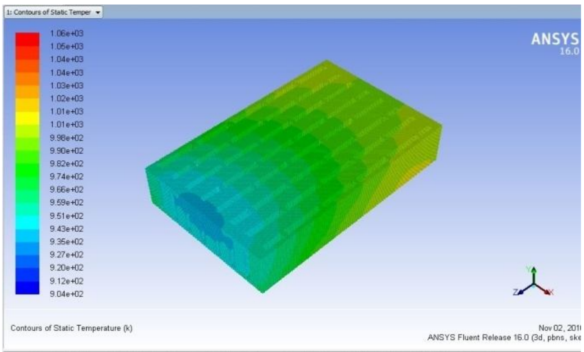


Fig6: Temperature distribution of steel HE at mass flow rate of 0.001983kg/m3

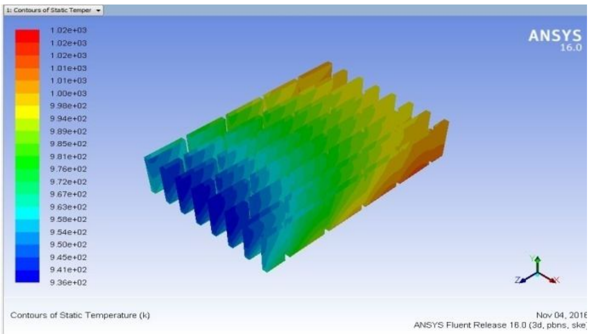


Fig7: Temperature distribution of INCONEL HE at mass flow rate of 0.001983kg/m3

Calculations Based On Simulation Results

Effectiveness (ϵ):

$$\varepsilon = \frac{(\dot{m}\, c_p)\ (T_{c,out} - T_{c,in})}{(\dot{m}\, c_p)_{\min}\ (T_{h,in} - T_{c,in})}$$

Mass flow rate of air = 0.001983 kg/s
Mass flow rate of exhaust gas = 0.001983 kg/s
Exhaust gas inlet temperature = 1060K
Air inlet temperature = 904K
Specific heat of air = 1111.7 J/kg-K
Specific heat of water = 1138.7 J/kg-K

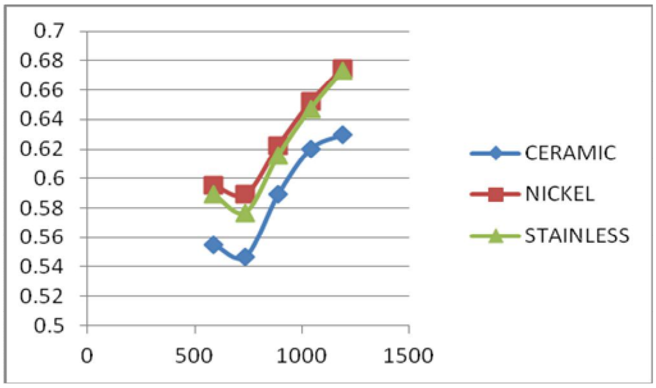
Effectiveness of Heat Exchanger with ceramic material:
At Mass flow rate of air = 0.001983 kg/s

Air outlet temperature = 990.7 K
Exhaust gas outlet temperature = 983.11 K
Actual heat transfer = $(mc_p)_{air}(T_{air\ out} - T_{air\ in})$ =2.2011(990.7-904)=190.8 W

Effectiveness (ϵ): = $(mc_p)_{air}(T_{air\ out} - T_{air\ in}) / (mc_p)_{min}(T_{gasin} - T_{air\ in})$
= (990.7-904)/(1060-904) = 0.555

Mass flow rate of air (kg/s)	Effectiveness & Actual Heat Transfer (W)	Heat Exchanger with cramic material	Heat Exchanger model with nickel inconel material	Heat Exchanger model with stainless steel material
0.001983	ϵ	0.555	0.595	0.589
	Q	190.8	204.39	202.5
0.002479	ϵ	0.547	0.589	0.577
	Q	192.5	207.4	202.9
0.002975	ϵ	0.589	0.622	0.6153
	Q	207.4	219.14	216.4
0.003471	ϵ	0.62	0.652	0.647
	Q	218.6	229.15	227.7
0.003966	ϵ	0.63	0.675	0.673
	Q	221.9	237.72	236.7

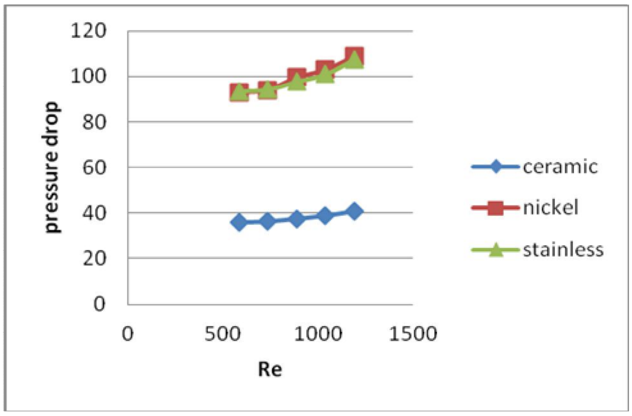
Table6: Effectiveness and Actual Heat Transfer for all cases



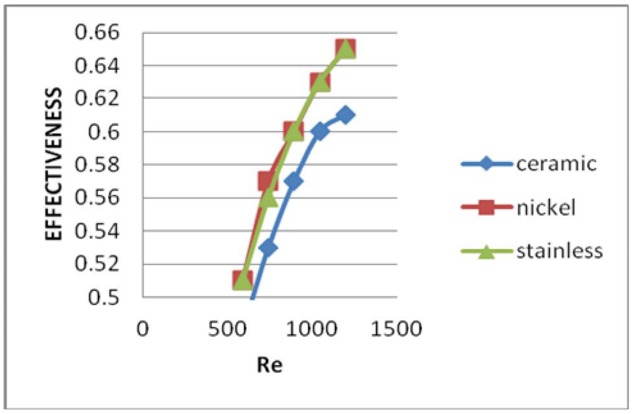
Graph1: Comparison of Effectiveness

effectiveness			
Re	CERAMIC	NICKEL	STAINLESS
585	0.555	0.595	0.589
736	0.547	0.589	0.577
888	0.589	0.622	0.6153
1040	0.62	0.652	0.647
1192	0.63	0.675	0.673

Table7: effectiveness with respective to Re



Graph2: Pressure drop on exhaust side with respective to Re.



Graph3: effectiveness with respective to Re.

IV. CONCLUSIONS

In this study, The numerical computations were carried out through hot exhaust, ceramic core , and cold air in the whole region of the ceramic heat exchanger for 800~1,000^0. The effectiveness and the outlet temperatures by the numerical computation were compared with those by ξ -NTU method using various Nusselt number correlations from literature.The relative errors of the temperature distribution by -NTU method higher than 2% to that by the numerical computation. Three types of materiel are compared to find out the optimum material for high temp carrying heat exchanger. INCONEL nickel 718 material material having more effeteness as compared to remaining materials. If mass flow rate increases the output temperature are decreases. According to pressure drop ceramic material are having minimum pressure drop as compared to reaming materials. Nickel alloy INCONEL 718 material heat exchanger can transder the more heat from exhaust side to air side. According to analytical and analysis results nickel alloy is best suitable for high temperature heat exchange.

REFERENCES

[1] Paeng JG, Yoon YH, Kim KH, Yoon KS. Theoretical and Numerical Analyses of a Ceramic Monolith Heat Exchanger. Journal of Mechanical Science and Technology. 2010; 24(7):1545–51.

[2] Nagarajan V, Chen Y, Wang Q, Ma T. Hydraulic and Thermal Performances of a Novel Configuration of High Temperature Ceramic PlateFin Heat Exchanger. Applied Energy. 2013; 113:589–602.

[3] Zeng M, Ma T, Sunden B, Trabia M B, Wang Q. Effect of Lateral Fin Profiles on Stress Performance of Internally Finned Tubes in a High Temperature Heat Exchanger. Applied Thermal Engineering. 2013; 50(1):886–95.

[4] De Mello PEB, Monteiro DB. Thermodynamic Study of an EFGT (Externally Fired Gas Turbine) Cycle with One Detailed Model for the Ceramic Heat Exchanger. Energy. 2012; 45(1):497–502.

[5] Monteiro DB, de Mello PEB. Thermal Performance and Pressure Drop in a Ceramic Heat Exchanger Evaluated Using CFD Simulations. Energy. 2012; 45(1):489–96.

[6] Gao Z, Liu Y, Gao Z. Heat Extraction Characteristic of Embedded Heat Exchanger in Honeycomb Ceramic Packed Bed. International Communications in Heat and Mass Transfer. 2012; 39(10):1526–34.

[7] Maa T, Wang Q-W, Zeng M, Chen Y-T, Liu Y, Nagarajan V. Study on Heat Transfer and Pressure Drop Performances of Ribbed Channel in the High Temperature Heat Exchanger. Applied Energy. 2012; 99:393–401.

[8] Cadavid Y, Amell A, Cadavid F. Heat Transfer Model in Recuperative Compact Heat Exchanger Type Honeycomb: Experimental and Numerical Analysis. Applied Thermal Engineering. 2013; 57(1–2):50–6.