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Three Dimensional Numerical Analysis of Ceramic Heat Exchanger

Chandrakala N S[1], Hanoca P[2], Naveena kumar R R[3]
[1]Student, [2]Asst. Professor, [3]Asst. Professor
[1] Dept. of Mechanical Engineering
[1]Rajeev Institute of Technology, Hassan, India

***Abstract* - The ceramic heat exchanger is studied to find the performance of heat transfer and pressure drop by numerical computation. The numerical computation was performed throughout the domain including fluid region in exhaust gas side rectangular ducts, ceramic core and fluid region in air side rectangular duct with the air and exhaust in cross flow direction. The main aim is to reduce the hot side temperature from 1100°c to 600°c and later it passes through the metallic heat exchanger temperature ranges less than 600°c. By increasing the Reynolds number on the cold air side this increase the velocity of the cold fluid Increase the heat transfer rate also increase the velocity by using nuzzling effect on cold air slot. The main purpose using the ceramic is to withstand with high temperature than metal.**

***Index term* – Ceramic heat exchanger, Cross flow, rectangular duct, nuzzling effect**

I. INTRODUCTION

A heat exchanger is a device that is used to transfer thermal energy 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. Typical applications involve heating or cooling of a fluid stream of concern and evaporation or condensation of single- or multi-component fluid streams. In other applications, the objective may be to recover or reject heat. Usually metallic or conventional heat exchanger withstand with temperature of 600°C. For higher temperature metallic heat exchanger cannot be resists. To overcome this problem ceramic heat exchanger are used because ceramic material can withstand with higher temperature.
In coal fired furnace or gas turbine exhaust gas temperature ranges from 1000°C to 1500°C. Therefore a recupertors or energy recovery equipment required to recover the high temperature heat. Accordingly heat resistance material is necessary for high temperature heat exchanger, and then exhaust passing through the ceramic heat exchanger temperature reducing from 1500°C to 500°C then it easily used in the metallic heat exchanger.
Computational Fluid Dynamics (CFD) is a powerful simulation tool to predict flow patterns, pressures, temperatures and concentrations in a vast range of applications. It can simulate behavior with the right fluids at the right scale and operating conditions. Unlike correlations and “black box” models, it gives a full three dimensional view inside or around the equipment. Because it is a simulation technology, it is safe, clean and nearly always cheaper and faster than experimentation**.** Optimize the design by using rectangular duct ceramic heat exchanger and numerical solution to the governing equations of fluid flow whilst advancing the solution through space and time to obtain a numerical description of the complete flow field of interest.

II. DESIGN AND ANALYSIS MODEL OF THE CERAMIC RECUPERATOR

The ceramic heat exchanger 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 Figure 2.1.

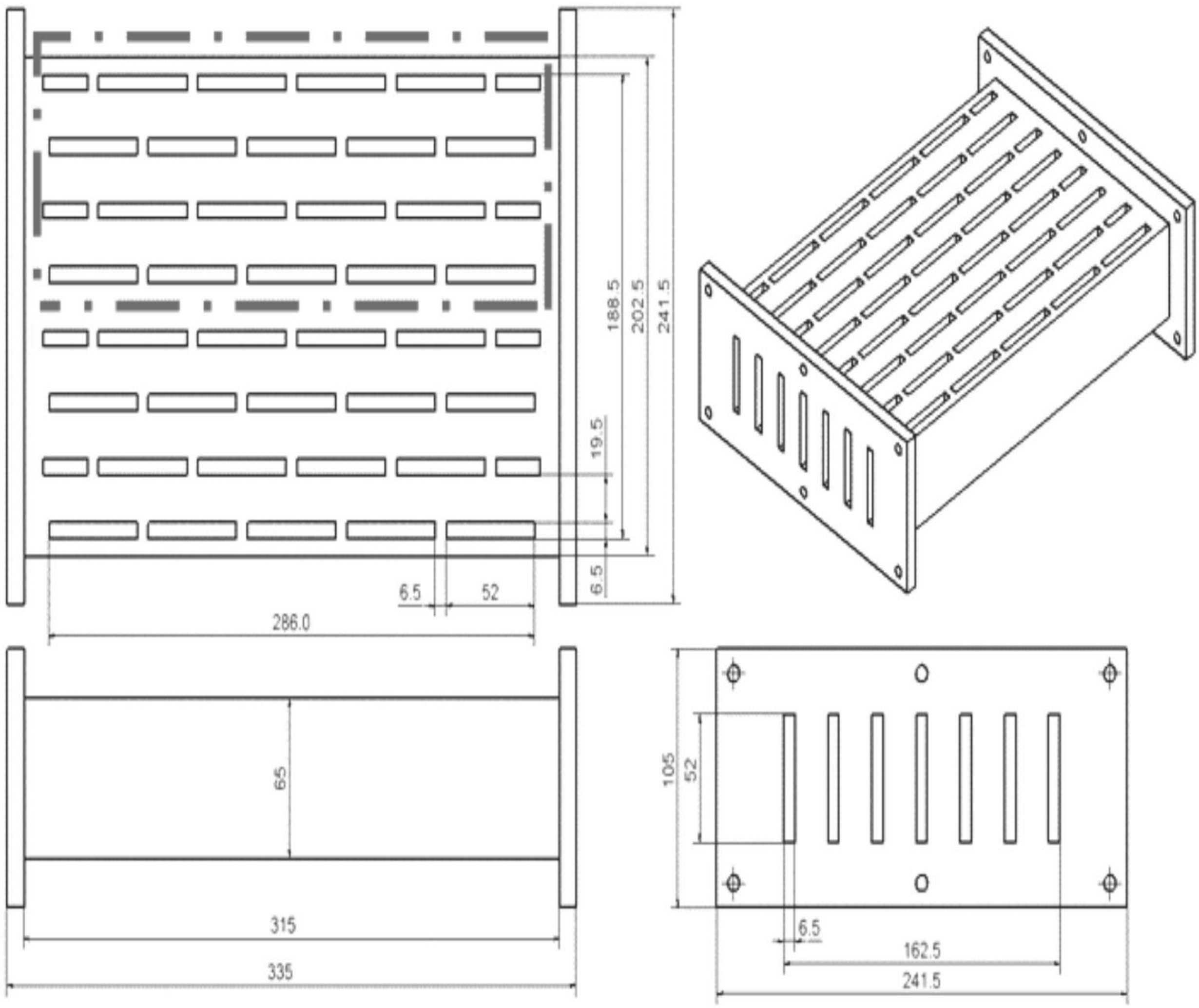

Figure 2.1 Schematic drawing of the ceramic heat exchanger (All dimensions are in mm)

2.1 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 /m^3.
7.	Specific heat of the ceramic material	670 J / kgK.
8.	Thermal conductivity of the ceramic material	77.5 W/mK.

2.2 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).

$$U = \frac{1}{\frac{1}{hair} + \frac{\Delta X}{k} + \frac{Aair}{\eta\ hgas\ Agas}} \qquad \text{……………….…(1)}$$

Here k is thermal conductivity of the ceramic core, ΔX is the thickness of the wall, and A_{air} and A_{gas} are the air-side and the exhaust-side heat transfer areas, and hair 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.

$$h = Nu * \frac{k}{Dh} \qquad \text{…………………...(2)}$$

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

ε-NTU Method

The thermal performance of the ceramic heat exchanger was calculated using a theoretical equation of the *ε –NTU* method in which the effectiveness (ε) is expressed as Eq. (3) for an unmixed fluid flow condition. These results were then compared to the numerical computation.

$$\boldsymbol{\varepsilon} = 1 - \exp\{ \frac{NTU^{0.22}}{C} [\exp(-CNTU_{0.78}) - 1]\} \qquad \text{…………………...(3)}$$

Here C represents the ratio of heat capacity (C_{min} /C_{max}). NTU is defined by the total conductance (*UA*) divided by the minimum heat capacity (C_{min}), where C_{min} is the lower heat capacity (mc_p)min and Cmax is the higher heat capacity (mc_p)max of the two fluids where m and cp are the mass flow rate and specific heat of the hot and cold fluids, respectively. Subsequently, the rate of heat transfer from hot to cold fluids can be computed as Eq. (4).

$$q = \varepsilon \times C_{min}(T_{gas\_in} - T_{air\_in}) \quad \text{..........................(4)}$$

Then the outlet temperatures of exhaust and air ($T_{air\text{-}out}$ and $T_{gas\text{-}out}$) are evaluated with the inlet temperatures of both fluids as Eq. (5) and Eq. (6).

$$T_{air\_out} = T_{air\_in} + q/ Cp_{\_air} \quad \text{......................(5)}$$

$$T_{gas\_out} = T_{gas\_in} + q/ Cp_{\_gas} \quad \text{......................(6)}$$

III. NUMERICAL ANALYSIS

There are few experimental data concerning the thermal performance of ceramic monolith heat exchangers. Therefore, numerical computations were necessary in order to assess the performance of the heat exchanger tested in this study. These were performed by computing conjugated heat transfers through the whole domain, including the fluid and ceramic solid region.

3.1 Boundary conditions

In this computation, a principal velocity profile at each inlet was assigned as uniform according to the mass flow rate, but the two velocity components perpendicular to the principal directions were assumed to be zero. The temperature was also assumed to be uniform, at inlet as Eq. (7).

$$T = T_{in} \quad \text{......................(7)}$$

Atmospheric pressure was given at each exit for the flow passages, since the exits are open to the atmosphere. For the boundary conditions of temperature at the exits, adiabatic conditions were imposed as Eq. (8).

$$\frac{\partial T}{\partial x} = 0 \quad \text{..............................(8)}$$

Non-slip conditions were applied on the walls of all fluid flows as Eq. (8). Adiabatic conditions were imposed at he outer walls of the ceramic core, except for the walls of the flow passages for cold air and hot exhaust as Eq. (9).

$$U_{wall} = V_{wall} = W_{wall} = 0 \quad \text{......................(9)}$$

Table 3.1 Fluid properties for CFD analysis (R_eD_h=585).

Properties	Air Side Mean Temperature 631 [℃]	Exhaust side Mean temperature 631[℃]
ρ [kg /m3]	0.391	0.340
Cp[J / kgK]	1111.7	1138.7
k [W/mK] 0.062 0.070	0.062	0.070
μ [kg /ms]	3.875×10^{-5}	4.300×10^{-5}

Table 3.2 Thermodynamic properties of ceramic core (Temperature: 400 ℃).

Properties	Ceramic core
ρ [kg /m3]	3100
Cp[J / kgK]	670
k [W/mK]	77.5

Before computations of problem, the thermodynamic properties of the heat exchanger were tested by assuming that, for two ways, one has constant properties at average temperature for both inlet and outlet and the other one is a linear function to the fluid temperature. Fig.3.1 shows the computations for these two thermodynamic properties assumptions. In this figure, the two results are close to each other, with the relative errors. Therefore, the Thermodynamic properties were assumed to be constant with an average fluid temperature. For reference, Table(3.1) presents the air properties at 631℃ and the exhaust properties at 787℃. Table (3.2) also presents the properties of the ceramic core made silicon carbide (SiC) that were assumed for the purposes of numerical computation. The numerical computations were carried out for the exhaust mass flow rate of 0.001983 kg/s, varying the air flow rate from 0.001983 kg/s to 0.003966 kg/s in five steps. The Reynolds numbers according to the mass flow rates are presented in Table (3.3). All Reynolds numbers are based on mean temperatures of inlet and outlet temperatures. For instance, Fig. 3.1 presents the contours of the temperature distribution of the air (a) and exhaust gas (b) assuming an airside Reynolds number of 585 and a gas-side Reynolds number of 79, which indicates that the mass flow rates of the air and the exhaust were the same at 0.001983 kg/s . The air (a) flows from the left side to the right side, so the air tempera ture increases, moving from the left inlet to the right exit. In contrast, the exhaust gas (b) flows from the bottom to top so that the temperature is cooled from the high inlet temperature to the low exit temperature.

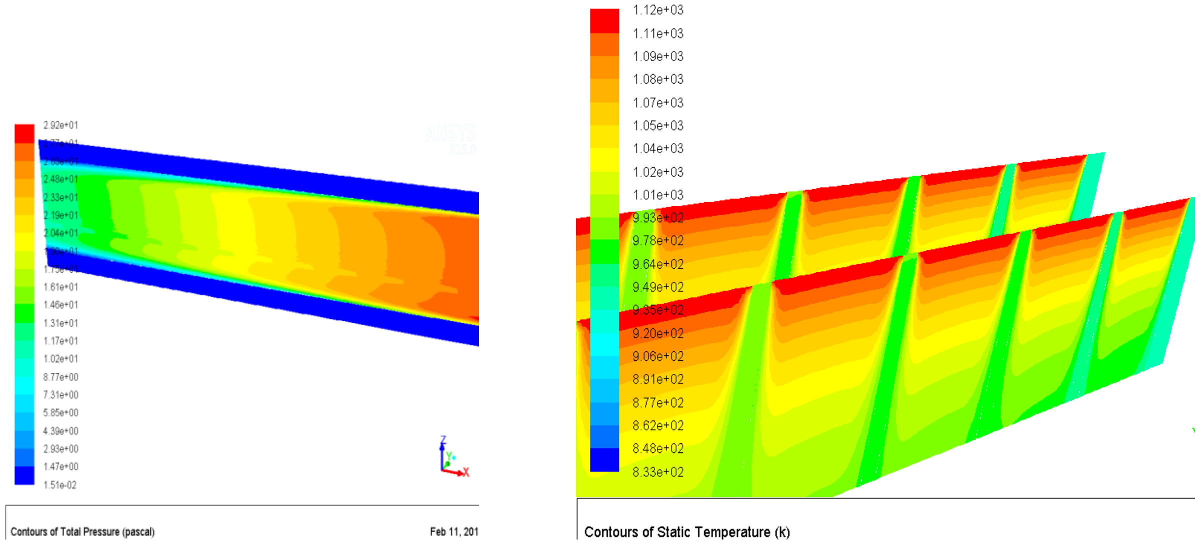

Figure 3.1. Contours of temperature distributions of air (a) and exhaust (b) flows [unit: K]

Table 3.3 Straight Cold Air Slot Heat Exchanger.

Straight cold air slot	Re Number	Velocity at cold side m/sce	Air inlet temperature (°k)	Air outlet temperature (°k)	Exhaust inlet temperature (°k)	Exhaust outlet temperature (°k)	Effectiveness ξ=((Tairout-Tairin)/(Tgasin-Tairin)) (%)	Effectiveness ξ=((Tgasin-Tgasout)/(Tgasin-Tairin)) (%)
	585	5.02	833	955.825	1123	975.655	0.4235	0.5081
	736	6.315	833	939.522	1123	966.166	0.3673	0.5408
	888	7.62	833	927.441	1123	959.154	0.3257	0.5650
	1040	8.924	833	918.207	1123	953.718	0.2938	0.5837
	1192	10.228	833	910.903	1123	949.319	0.2686	0.5989

Table 3.4 Nuzzling Effect (reducing the length 1mm at cold air exit).

Convergence 1 mm	Re Number	Velocity at cold side m/sce	Air inlet temperature (°k)	Air outlet temperature (°k)	Exhaust inlet temperature (°k)	Exhaust outlet temperature (°k)	Effectiveness ξ=((Tairout-Tairin)/(Tgasin-Tairin)) (%)	Effectiveness ξ=((Tgasin-Tgasout)/(Tgasin-Tairin)) (%)
	585	5.02	833	956.391	1123	973.351	0.4255	0.5160
	736	6.315	833	939.788	1123	963.518	0.3682	0.5499
	888	7.62	833	927.498	1123	956.284	0.3257	0.5749
	1040	8.924	833	918.002	1123	950.704	0.2931	0.5941
	1192	10.228	833	910.195	1123	946.209	0.2673	0.6096

Table 3.5 Nuzzling Effect (reducing the length 2mm at cold air exit).

Convergence 2 mm	Re Number	Velocity at cold side m/sce	Air inlet temperature (°k)	Air outlet temperature (°k)	Exhaust inlet temperature (°k)	Exhaust outlet temperature (°k)	Effectiveness ξ=((Tairout-Tairin)/(Tgasin-Tairin)) (%)	Effectiveness ξ=((Tgasin-Tgasout)/(Tgasin-Tairin)) (%)
	585	5.02	833	956.796	1123	971.0414	0.4269	0.5240
	736	6.315	833	940.092	1123	960.8355	0.3693	0.5592
	888	7.62	833	927.498	1123	953.3605	0.3259	0.5850
	1040	8.924	833	917.841	1123	947.6262	0.2926	0.6047
	1192	10.228	833	910.195	1123	943.0336	0.2662	0.6206

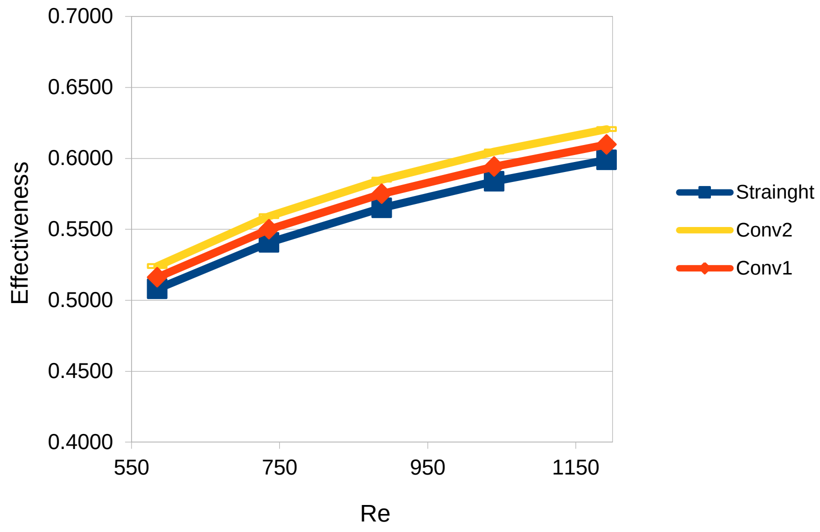

Figure 3.2. Comparison of the effectiveness between the numerical computation and ε-NTU method with various correlations of the Nusselt number (gas side Reynolds number: 79).

IV. CONCLUSION

In this study Computational Fluid Dynamics analysis were carried out for the hot exhaust, ceramic core, and cold air in the ceramic heat exchanger then to improve the heat transfer rate of ceramic heat exchanger, nuzzling effect is considered for cold flow side i,e outlet thickness has reduced by 1mm and 2mm respectively .from the results it clear that hot side effectiveness or exhaust gas effectiveness improved by nuzzling effect. Cold side effectiveness are improved but not as like as the hot side reduction in pressure loss also happening by the nuzzling effect, slight pressure loss increment is happening in the cold flow due to the nuzzling effect but compare with the effectiveness increment pressure loss negligible.

V. REFERENCES

[1] Ahmet Polata, Ozkan Sarikayaa, ErdalCelikb "Effects of porosity on thermal loadings of functionally graded Y_2O_3–ZrO_2 NiCoCrAlY coatings", March (2002).

[2] Anthony Hechanova University of Nevada, Las Vegas "High Temperature Heat Exchanger Annual Report", (2008).

[3] A. Summers Q. Wang, X. Han, Y. Parkd, A. Jacobi "Ceramics and ceramic matrix composites for heat exchangers in advanced thermal systems", A review Applied Thermal Energy PP 1-15, (2010).

[4] Ceramic Heat Exchangers Applied To an Aluminum Reverberatory, (2013).

[5] Dimasthoni stirimis, volkaruhlig "new ceramic heat exchanger with enchanced heat transfer properties for recuperative gas burner applied thermal energy", Applied Thermal Energy, (2008).

[6] Huisheng Zhang, Shilie Weng and Ming Su "Compact Heat Exchange Reformer Used for High Temperature Fuel Cell Systems", Applied Energy, (2010).

[7] Jin Gi Paeng, Kyung Hwan Kim and Young Hwan Yoon" Experimental measurement and numerical computation of the air side convective heat transfer coefficients in a plate fin-tube heat exchanger", Journal of Mechanical Science and Technology 23 536~543, (2009).

[8] M.Sudheer, g. Vigneshshanbhag, Prashanthkumar and ShashirajSomayaji "finite element analysis of thermal characteristics of annular fins with different profiles'', ARPN Journal of Engineering and Applied Sciences VOL. 7, NO. 6, JUNE (2012).

[9] Qi Li, Gilles Flamantb, XigangYuana, Pierre Neveub, "Compact heat exchangers: A review and future applications for a new generation of high temperature solar receivers", Applied Thermal Energy PP 15 4855-4875, (2010).

[10] Rahul Nandi, Santanu Bandyopadhyay, Rangan "Analysis of High Temperature Thermal Energy Storage for Power Plant", IEEE ICSET, (2012).

[11] R.J. Goldstein, W.E. Ibele, S.V. Patankar, T.W. Simon, T.H. Kuehn, P.J. Strykowski, "Heat transfer International Journal of Heat and Mass Transfer",PP 49 451–534,(2006) .

[12] Ting Maa, Qiu-wang Wang, Min Zeng a Study on "heat transfer and pressure drop performances of ribbed channel in the high temperature heat exchanger'', Applied Energy PP 99 393–401,(2012) .

[13] Vijaisri Nagarajan Numerical study of "a novel fin configuration of a high temperature ceramic plate fin heat exchanger", (2014).

[14] Vijaisri Nagarajan, Yitung Chen, Qiuwang Wang "Hydraulic and thermal performances of a novel configuration of high temperature ceramic plate-fin heat exchanger", Applied Energy 113 589-206 (2014).

[15] Yong Shuai, Fu-Qiang Wang, Xin-Lin Xia and He-Ping Tan Ray "Thermal-Structural Coupled Analysis of Parabolic Trough Solar Collector",(2009).