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Thermal Analysis Of Ceramic Heat Exchanger Using Simulation Techniques

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Abstract: - *There is a potential demand for heat exchangers capable of supporting working temperatures well above 900°C. Many different studies in the literature consider these components as critical for the implementation of externally fired gas turbines (EFGT) and externally fired combined cycles (EFCC). It is common sense that ceramics are the only alternative for the construction of these heat exchangers, but most part of the literature about heat exchangers usually considers only metallic materials for its construction. Consequently, the design of ceramic heat exchangers is not trivial and represents an actual technical challenge. In addition, different heat transfer modes are present simultaneously and as we all know that the geometry of heat exchanger decides the effectiveness of heat exchanger, two geometries are compared and discussed in this work. As a step in this direction, the present work presents the design of a ceramic heat exchanger using CFD and finite element structural simulations. The heat exchanger designed presents small dimensions in order to make it easier to construct a prototype and test it in the future.*

Keywords: **-** Ceramic heat exchanger, EFGT, EFCC.

I. INTRODUCTION

Heat exchangers are used in many commercial applications and numerous types can be purchased from a large number of manufactures. Recently, power generation has been exposed to the problems of the exhausts from fossil fuels and global warming. Therefore, the use of renewable energy and the development of nuclear energy have become more important. But, under existing conditions, they are not available, because the exploitation of renewable energy is small compared with the total amount of energy consumed, and nuclear energy is associated with safety issues. Above all, it is important to get rid of the dependence on oil fuel, and usage of coal, which is on the other hand abundant all over the world. In addition, the efficiency of power generation must be improved. High temperature heat exchanger technology has become important for improving the performance of power generation. Many in the field have been counting on the development of a heat exchanger for generating high temperature gas. But, it is difficult for the conventional metal heat exchanger to be used at high temperatures or with corrosive gases. Metal heat exchangers have limits in their usage. Ceramic exchangers may meet these limits. Under existing conditions, however, the difficulty of manufacturing complicated surfaces with ceramics has prevented the wide spread use of such exchangers. As geometric constraints are particularly important for such a gas reactor to limit the size of the primary vessels, compact heat exchangers operating at high pressure and high temperature are attractive potential solutions for recuperator applications. Today, the diffusion bonded heat exchangers with micro-channels appear to a more promising concept for recuperator application.

One of the promising applications for HTHEs is in the power industry, because they would turn possible the implementation of EFGT (externally fired gas turbines) and EFCC (externally fired combined cycles). The typical arrangement of the components of one EFGT cycle is shown in Fig. 1. As stated by Kautz and Hansen (2007), the key component in the cycle is the HTHE, because the other components are standard parts. In both of these cycles the combustion flue gases don’t pass through the turbine so that other fuel than gas can be used, like biomass or coal.

One ceramic plate-fin HTHE was designed by Fischedick et al (2007) for 50kWth and many important design considerations were evaluated, such as: the choice of the ceramic material; structural integrity of the heat exchanger; thermal design; pressure drop introduced by the heat exchanger, and others that will be addressed in the present study.

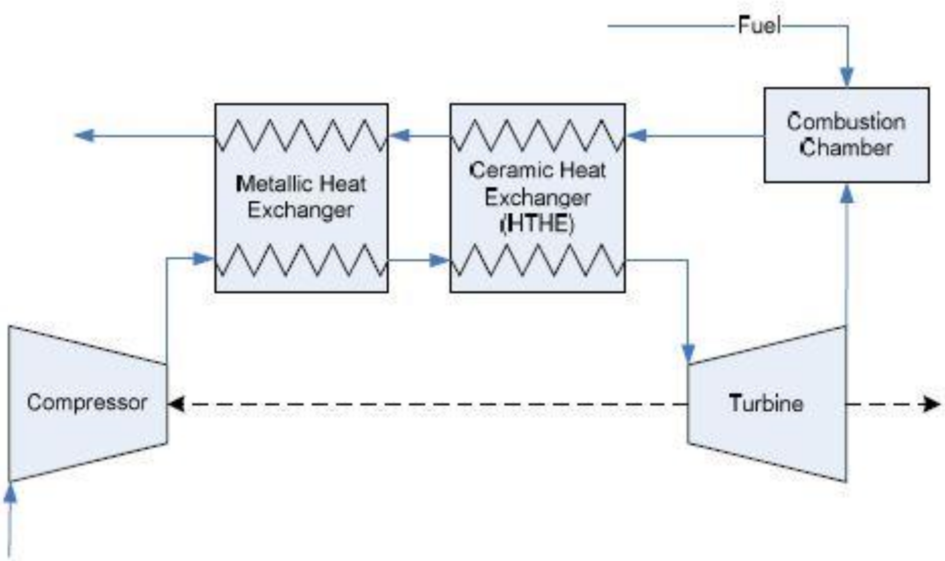

Fig.1

Pressure drop produced by the heat exchanger deserves special attention during design stage because it reduces the thermal efficiency of the cycle (Kautz and Hansen, 2007). The challenge in the design of a ceramic HTHE for power applications is to achieve high effectiveness without producing high pressure drop. It is considered a difficult task since the same heat capacity rate is observed in both sides of the heat exchanger.

II. OBJECTIVES

The design comparison of two different models of a ceramic heat exchanger is presented and discussed in the present work. The design is conducted considering a very small heat exchanger that could be tested in a laboratory bench work, producing useful data for the validation of the presented design methodology. The final prototype should have external dimensions smaller than 100 mm.

The design of the heat exchanger is aiming at a particular application: the EFGT, but it doesn't consider significant pressure differences between the hot and cold sides, which would introduce one extra difficulty for the future experimental tests. Besides, other characteristics of the application are maintained: air is the fluid in both sides of the heat exchanger and the flow rate is the same for the hot and cold sides. This condition, as discussed later, will present limitations to the effectiveness that can be obtained for the heat exchanger.

2.1 Potential applications and requirements

The requirements for the design phase were drawn out following a detailed analysis of four different potential applications (Luzzatto [1997]) for a maximum temperature of 1500 °C, a maximum pressure of 2.5 MPa and a maximum differential pressure between gases of 0.6 MPa. The applications are:

- **Chemical**: a syngas production plant. Different syngas production processes have been considered leading to the choice of the scheme implemented in the Puertollano IGCC plant (Prenflo process).

- **Metallurgical**: an aluminum reheating furnace. Estimations from US sources show a very attractive market for this application, in which metallic recuperators suffer from very high corrosion.

- **Glass**: a typical production plant. The air preheating system can be changed from the regenerative type to the recuperative, and electric energy can be produced.

Waste: a waste incineration plant. Heat recovered from downstream of the incinerator is used in an indirect-fired

2.2General design considerations

- For high temperature heat exchangers, the thermal stresses during the startup, shutdown and load fluctuations can be significant. Heat exchanger must be designed accordingly for reliability and long life.
- The thermal capacitance ("thermal mass") should be reduced for high temperature heat exchangers for shorter startup time.
- High temperature heat exchangers require costly materials contributing to the high cost of balance of power plant. Heat exchanger cost increases significantly with temperature above about 675°C.

III. SELECTION OF MATERIALS FOR HTHES

Three major classes of high-temperature materials are promising candidates for different applications:

High-temperature nickel-based alloys (e.g., Hastelloy). Good material compatibility potential for helium and molten salts up to temperatures in the range of 750°C. Also a candidate material for sulfuric acid thermal decomposition. Limited capability under fusion neutron irradiation.

High-temperature ferritic steels (particularly oxide- dispersion ferritic steels). Good performance under fusion and fission neutron irradiation, to temperatures around 750 °C Good potential for compatibility with lead/bismuth under appropriate chemistry control. Demonstrated compatibility with molten salts would have substantial value for the fusion application. Silica bearing steels provide a candidate material for sulfuric acid thermal decomposition.

Advanced carbon and silicon carbide composites. With excellent mechanical strength to temperatures exceeding 1000°C, these are now used for high temperature rocket nozzles to eliminate the need for nozzle cooling and for thermal protection of the space shuttle nose and wing leading edges. Many options are available that trade fabrication flexibility and cost, neutron irradiation performance, and coolant compatibility. These materials can potentially be used with helium and molten salt coolants. Silicon carbide is also compatible with sulfur-iodine thermochemical hydrogen production. Major opportunities and research challenges exist to apply these materials to high-temperature heat transport applications.

The best material available seems to be a SiCp/Al2O3, (particles reinforcing phase-based material), from a US manufacturer; no European manufacturer could supply Ceramic Matrix Composites (CMC) bayonet tubes.

IV. THERMAL DESIGN

In the work of Fischedick et al (2007), the thermal design of the HTHE was conducted by using correlations for theColburn and friction factors for offset strip fins. These correlations were obtained from experiments by Manglik andBergles (1995).

The present work uses CFD simulations for the thermal design task. This choice can be justified by the possibility of considering the heat conduction in the ceramic material coupled with the convective heat transfer, technique known as conjugate heat transfer. This type of simulation is particularly important since it can provide the temperature distribution in the ceramic material as a result that can be used as input to the structural design.

The number of transfer units (NTU) method is used for the present analysis and design. The theory related to NTU can be found in many texts from literature. It states that the effectiveness ε depends on the number of heat transfer units NTU and the heat capacity rates of the hot and cold flows Cr. This dependence is summarized by Eq. (1).

$$\varepsilon = \varepsilon\,(NTU, Cr) \qquad (1)$$

The number of transfer units (NTU) and the ratio between heat capacity rates are given by Eq. (2) and (3), respectively.

$$NTU = UA/C_{min} \qquad (2)$$

$$Cr = C_{min}/C_{max} \qquad (3)$$

Here, U is the overall heat transfer coefficient, A is the heat transfer area, and Cmin and Cmax are the minimum and maximum capacity rates.

The heat exchanger designed in the present work is very similar to the one presented by Fischedick et al (2007), but its dimensions are much reduced, for the reasons already commented in the design objectives section. The heat exchanger is formed by ceramic plates that are stacked. The geometry of the ceramic plates can be seen in Fig. 3 and its dimensions were a result of the following criteria: the thickness of any plate region should not be less than 5 mm; the external dimensions of the mounted heat exchanger should be smaller than 100 mm.

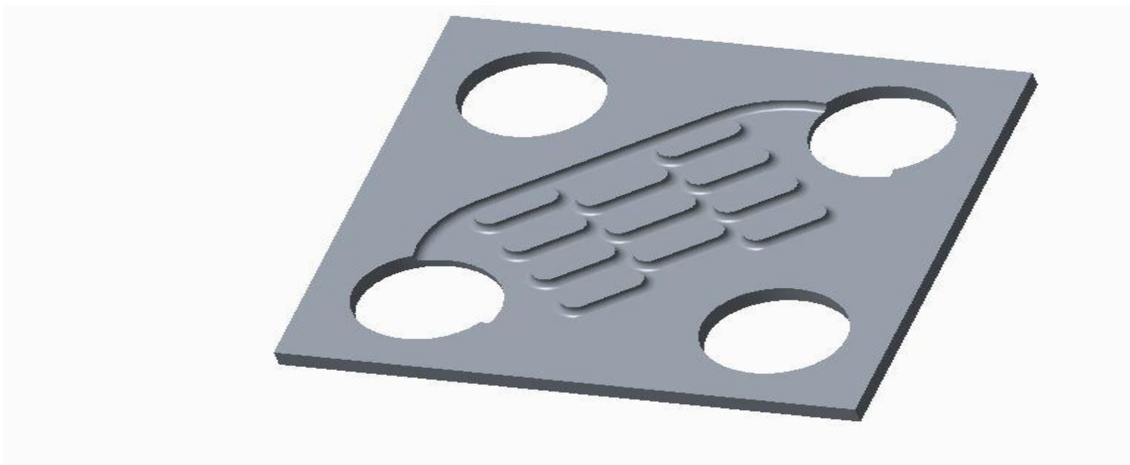

Fig.2 Rectangular duct with elliptical pins

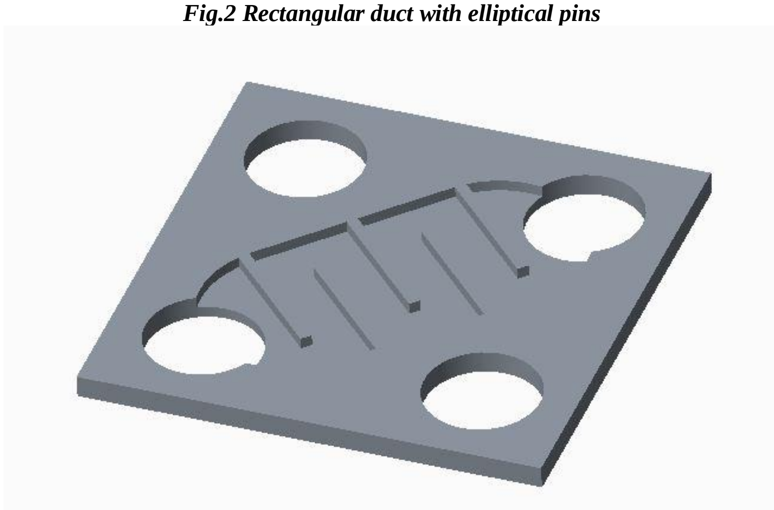

Fig.3 Rectangular duct with pins arranged in serial pattern

4.1. CFD Simulations

All the CFD simulations were conducted using ANSYS FLUENT 15.0 and modeling of plates has been done in CREO 3.0 The convergence criteria was set to RMS of the residuals lower than 5×10-5. The high order interpolation scheme was used. The Reynolds number, based on the 5.0 mm channels shown in Fig. 3, is between 200 and 1000, depending on the flow rate. Therefore, no turbulence model was needed. The density variation with temperature is very significant for the application considered herein and it was considered in the simulations with ideal gas model. considering only the air flow through the channels (without conjugate heat transfer). The number of elements in the grids varied from 1.8 to

2.7 millions. The results have not shown asymptotic behavior, but the difference observed between the highest and lowest heat transfer rate was smaller than 30% (120.58 W and 176.576 W respectively) in case of elliptical pins rectangular duct and in case of serial pins rectangular ducts followed the same trend but heat transfer rates are slightly low. It produced differences over the effectiveness of almost 1% considered satisfactory but effectiveness is just more with 0.97 in case of serial pins rectangular duct against 0.96 in case of pins rectangular duct.

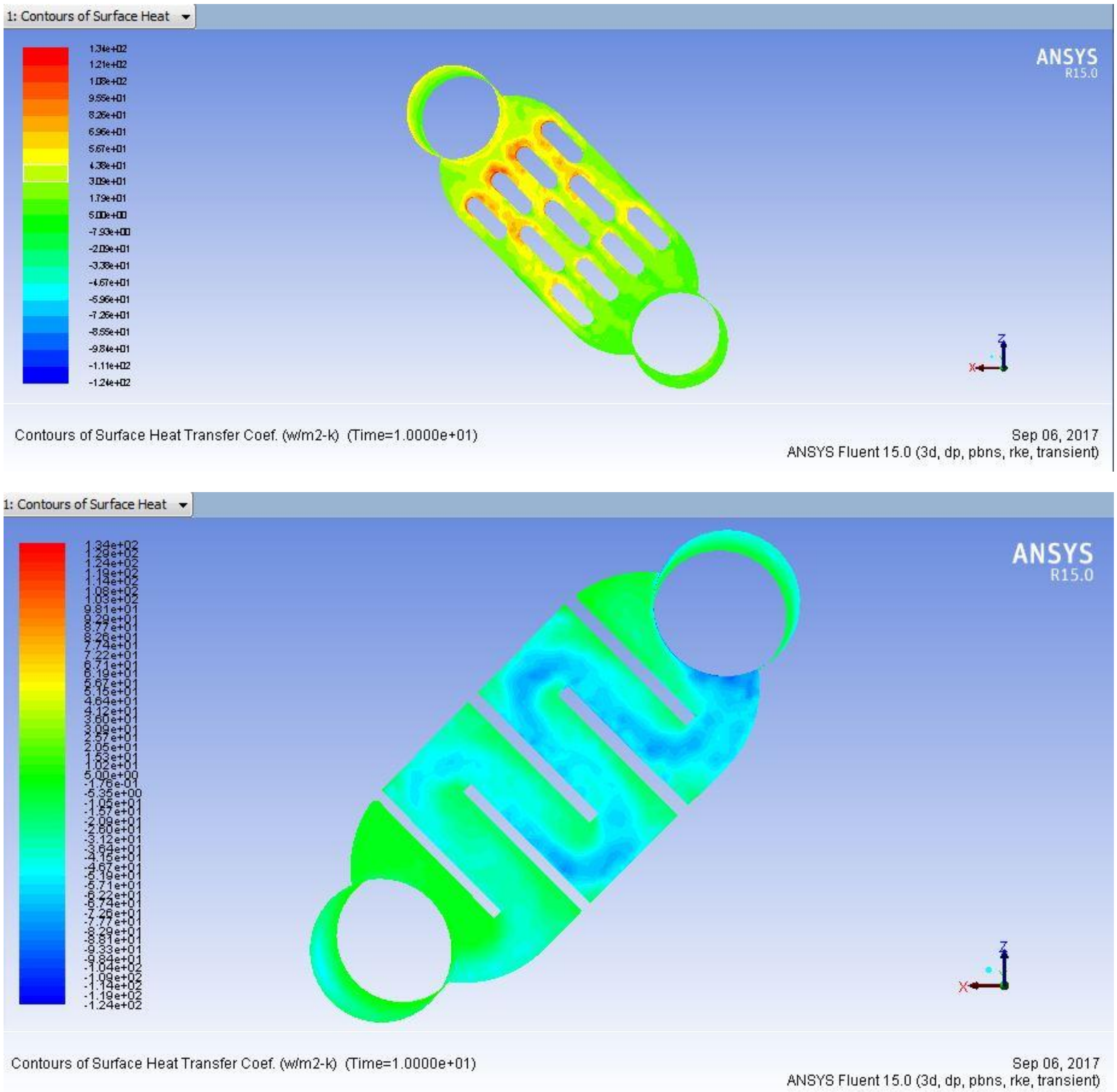

Fig.4 Contour of local heat transfer coefficient (air is flowing from left to right)

The results obtained with a typical simulation, are presented in table 2. For this ideal condition the overall heat transfer coefficient is equal to the average heat transfer by conduction

	ELLIPTICAL MODEL			ELLIPTICAL AND SERIAL BAFFELE ARRANGEMENT		
mass flow rate (kg/s)	HEAT TRANSFERRED TO COLD FLUID	EFFECTIVENESS	COLD FLUID OUTLET TEMPERATURE (K)	HEAT TRANSFERRED TO COLD FLUID	EFFECTIVENESS	COLD FLUID OUTLET TEMPERATURE
3.00E-04	120.57307	0.9644	568.76331	116.73681	0.9073	554.98486
4.00E-04	150.20998	0.9659	557.23462	142.80825	0.9383	544.35583
5.00E-04	176.58465	0.9659	544.76093	165.75339	0.9713	538.02991

Under real conditions, where Cr is close to unity, the effectiveness should be significantly lower. It suggests that the effect of the flow rate over the effectiveness could be evaluated with the ideal model before dealing with the much demanding model, using conjugate heat transfer.

Following this approach, a series of simulations with different flow rates was conducted. When the flow rate is reduced, the overall heat transfer coefficient U and the heat capacity rate Cmin decrease. Due to this behavior, it is not obvious the effect of the flow rate over NTU. But the graph of Fig. 5, which summarizes the results, shows clearly that NTU increases when flow rate is reduced. In other words, Cmin decreases faster than U when the flow rate is reduced, at least for the heat exchanger considered here.

Of course, another option to increase NTU would be to increase heat transfer area, but it is not in agreement with the objectives of the present work, . considering the limitations imposed to the size of the heat exchanger. The effectiveness, varied from 0.9644 to 0.9659 for elliptical pins rectangular duct and the same varied from 0.9073 to 0.9713 for serial pins rectangular ducts when the flow rate is increased from 3×10-4 kg/s to 5.0×10-4 kg/s

Conjugate heat transfer simulations were conducted including the effect of heat conduction in the ceramic walls. The steady state simulations considered the heat conductivity of alumina k = 11.4 W/m K, according to data from NIST (2010). Figure 6 shows the stacked arrangement of the plates. The geometry of each plate was already shown in Fig. 3. Only one pair of plates was simulated and periodicity boundary conditions were used in order to approximate the stacked plate arrangement. Periodic boundary condition means that, for calculation purposes, the bottom side of the pair of plates is in contact with the top side of an adjacent pair. This boundary condition is used only for the solid domain.

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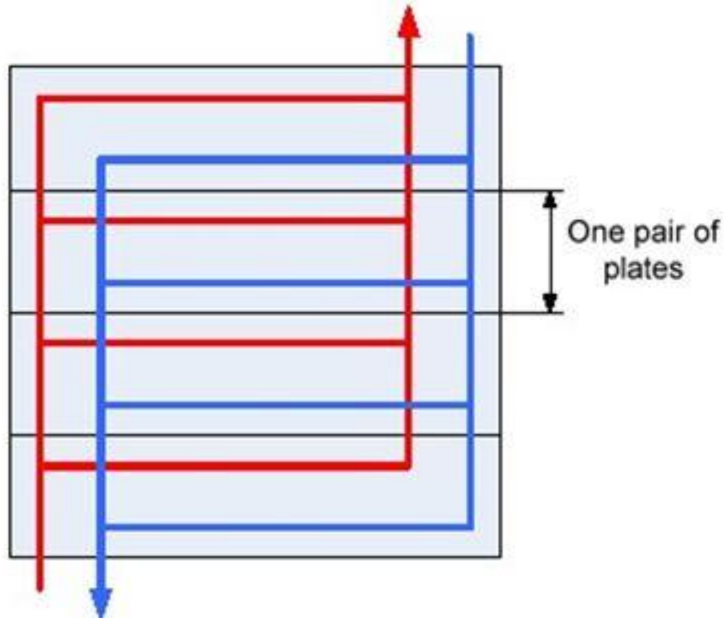

Fig.5 Scheme of the stacked ceramic plates. Only one pair of plates is considered in the simulation

For the fluid domains, temperatures and flow rates are imposed in the inlets of the heat exchanger. Different flowrate conditions were simulated, but maintaining equal flow rates on cold and hot sides for each condition. Temperatures imposed to the inlet flows of the cold and hot sides are respectively 30°C and 1000°C.

The most important result of each simulation is the temperature of the air leaving the heat exchanger, in hot and cold sides. These results allow the calculation of a series of derived results: effectiveness, NTU, among others.

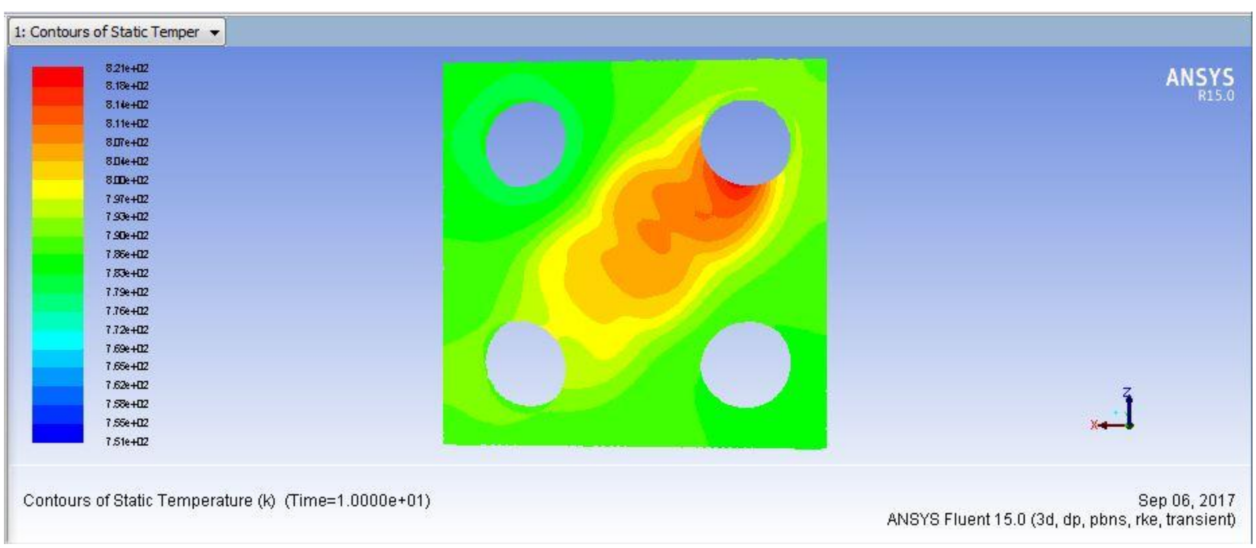

Fig.6 Temperature distribution in the ceramic plates (°C).

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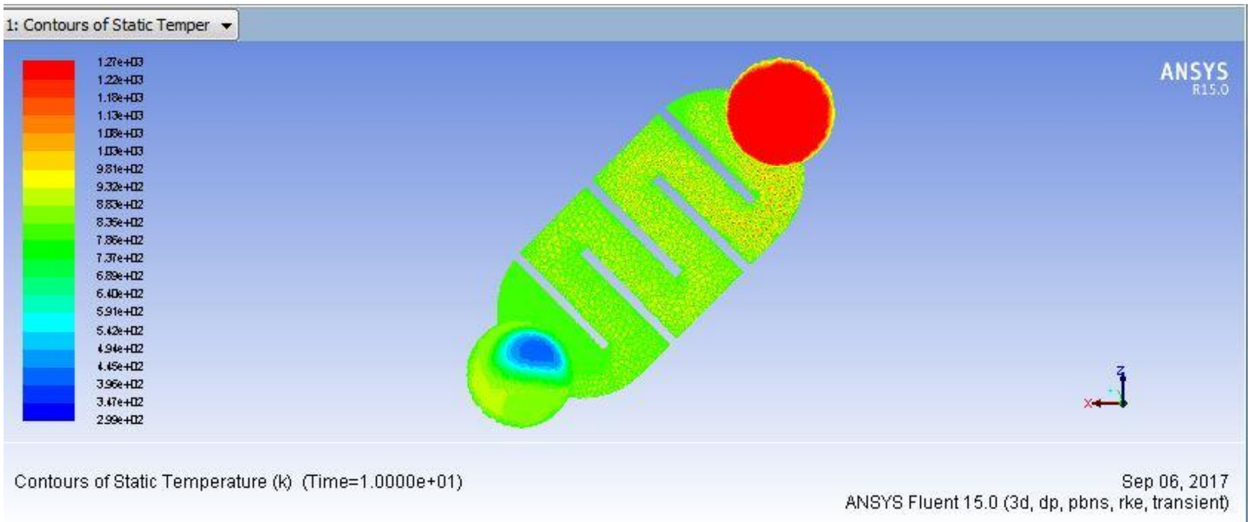

Fig.7 Temperature contour of hot side fluid in serial pins rectangular ducts

V. CONCLUSIONS

This work presented a procedure for the design of a ceramic heat exchanger of very small dimensions. In the future, the construction and test of the heat exchanger is intended, in order to validate the design methodology and gain further insight to extend it to practical applications.

The low effectiveness obtained with the design can be attributed to the cross flow configuration and comparatively high convective heat transfer coefficients resultant from k-ε turbulent model. The thermal resistance by conduction in the ceramic walls is not significant for the design simulated.

Amount of heat transferred is less in case of serial pins rectangular ducts when compared to elliptical pins rectangular duct due to difference in duct width. but the effectiveness is more due to the time lag in flow. also pressure drop is less in case of serial pins with rectangular duct when compared to elliptical pins with rectangular duct.

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