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Stress Study on Different Designs of Ceramic High Temperature Heat Exchangers

Ting Luo, Ting Ma, Min Zeng, Qiuwang Wang*

Key Laboratory of Thermo-Fluid Science and Engineering, MOE, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049, P.R.China
wangqw@mail.xjtu.edu.cn

As the growing depletion of energy and resource, there is an increasing need to improve the fuel utilization efficiency, and in many cases it can only be achieved by improving the operating temperatures. As the leading material for high temperature, ceramics are proposed to fabricate heat exchangers used for high temperature exhaust heat recovery and other industrial applications. Due to the extreme operating condition, it's essential to analyze the thermal stress distribution and reduce the overall stress level to ensure their operating safety. In this paper, the thermal stress performances of common and new designed ceramic plate heat exchangers are presented. According to the results, the maximum thermal stress is found on the corners and connection regions. Some structure modifications are proposed for the common plate designs to protect its joint regions and the cracks are predicted to generate initially at the outer surface of the primary surface plate.

1. Introduction

The price of fossil fuels is increasing significantly due to energy crisis. To increase fuel utilization efficiency and decrease energy consumption becomes more and more important, and it can always be realized by improving the thermal efficiency of heat transfer system. Taking use of the waste heat is a usual method to attain a high overall thermal efficiency. For many high temperature applications, ceramic heat exchangers is a good choice, and it may be the only way to achieve ultimate performance potential for microturbines (McDonald, 2005).
Ceramic materials have many advantages compared with other materials. Due to its excellent high temperature capability and oxidation resistance, ceramics can be applied in harsh environments where alloys are unsuitable. Ceramics have been used in many applications, including high temperature heat exchangers. Advances in ceramic technology offer more opportunities and results in greater versatility in providing better engineering solutions (Sommers et al., 2010).
Fine designed heat exchangers often has better performance, lower operating costs and prolonged lifetimes compared with a rough designed one. A lot of factors should be taken into consideration in ceramic heat exchanger design. Ponyavin et al. (2008) investigated the flow maldistribution problem inside a ceramic heat exchanger and a better design was proposed which can achieve sufficient uniform flow rate distribution with appropriate pressure drop. Several other configurations were also studied on their heat transfer characteristics (Kee et al., 2011; Alm et al., 2008). Due to the intrinsic brittleness of ceramic materials, thermal stress distribution and reliability of heat exchangers is also explored (Schulte-Fischedick et al., 2007; Islamoglu, 2004;). However, few open papers have been published on the effect of different structure designs on the thermal stress distribution.

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Most of recent researches on the ceramic plate fin heat exchangers focus on straight channel and offset-strip fins, and its typical cross section is shown in Figure 1. Primary surface is a common plate structure used for recuperators in microturbines. Due to its excellent heat transfer efficiency and compactness, primary surface is proposed to be used for ceramic high temperature heat exchanger. Ceramic primary surface plate is also easier to be manufactured by mould because of its smooth and slick surface compared with ceramic fins plate.

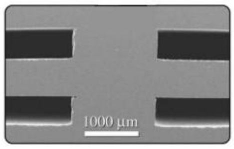

Figure 1: Typical cross section of ceramic plate heat exchangers (Kee et al., 2011)

In this paper, the thermal stress distributions of several plate designs are investigated. After comparison of 2D models, a 3D model with periodic plate changes in the streamwise direction is studied for comparison. According to the results, some changes are proposed for plate designs, the results also reveals the stress distribution in different designs.

2. Numerical model and methods

2.1 Numerical model and boundary conditions

The maximum thermal stress often lies in the locations with the maximum temperature difference. So in this paper, 2D investigations only focus on the locations behaving the maximum temperature difference, and in most cases, this districts lies in the inlet and outlet of heat exchangers. The present ceramic heat exchanger core manufactured has typical cross-section shape as shown in Figure 1, Due to the symmetry inside the heat transfer core, only ceramic plates with half of the hot and cold flow channels are chosen for computation. As shown in Figure 2, the first two designs (the 1st and 2nd design) are extracted from the common designs with different straight channel sintered arrangement, the thickness of the plate is 1 mm, and the height of each fin is 2 mm. The last two designs represent the primary surface plate designs. The 3rd plate design has consistent thickness, 1 mm, but the diameters in two sides are not consistent. The 4th design, like the cross section of plate shown in Figure 3, has the same diameters in both sides but different plate thickness.

Only the inlet is taken into account to study the maximum temperature and thermal stress distribution. The hot and cold fluid temperatures are supposed to be kept at 1000 K and 400 K respectively. The convection heat transfer coefficients on each side is assumed to be 60 W·m^{-2}·K^{-1}, which is according to the results of computation previously. The properties of ceramic materials used in 2D simulation are given in Table 1 (Islamoglu, 2004).

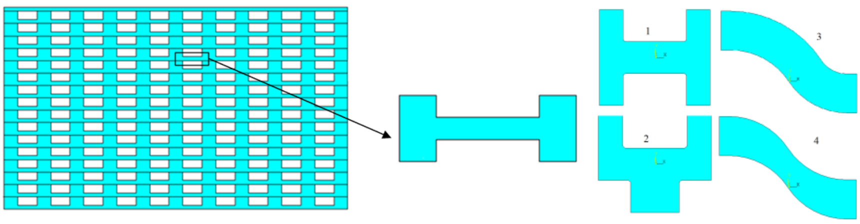

Figure 2: Extraction of computing model from the heat transfer core and four different plate designs

For comparison of the stress distribution, a new offset bubbles primary surface ceramic plate is investigated. As shown in Figure 3, it has periodic geometric changes along the streamwise direction. The plate thickness *T* is 1 mm, the width of the module *W* is 3 mm, and the wavelength of the module *L* is 24 mm. A 3D model is selected in order to study the thermal stress distribution of the offset bubbles primary surface plate. The plate model selected is 216 mm long and has 9 modules in the streamwise direction, as shown in Figure 4. The temperature field of ceramic plate is obtained from FLUENT and will be mapped onto the finite element mesh to compute the temperature and thermal stress distribution. In all computations, the ceramic materials are supposed to be isotropic.

Table 1: Materials properties of SiC ceramics (Islamoglu, 2004)

Young's modulus,(GPa)	427
Possion ratio	0.17
Thermal expansion coefficient,($10^{-6}K^{-1}$)	4.8
Thermal conductivity,($W \cdot m^{-1} \cdot K^{-1}$)	42
Density,($kg \cdot m^{-3}$)	3210
Specific heat capacity,($J \cdot kg^{-1} \cdot K^{-1}$)	2540
Tensile strength,(MPa)	950

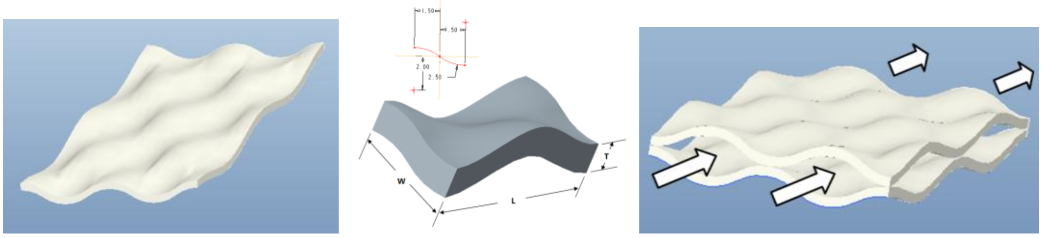

Figure 3: The new offset bubbles primary surface plate design and one module /mm

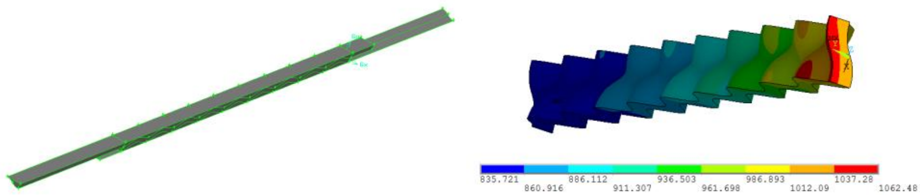

Figure 4: The heat transfer model in FLUENT and the temperature distribution obtained/K

2.2 Numerical methods

The temperature distribution and thermal stresses are calculated using a finite element method with a commercial software ANSYS. Element plane 77 and solid 70 is chosen to compute the temperature distribution. Then it is transformed to plane 183 and solid 185 respectively to calculate the thermal stress for 2D and 3D models. In 2D models, only convection heat transfer boundary conditions are loaded on the surfaces of each sides, all other edges are symmetry and heat fluxes are kept at zero. Figure 5 shows the boundary conditions used in stress analysis.

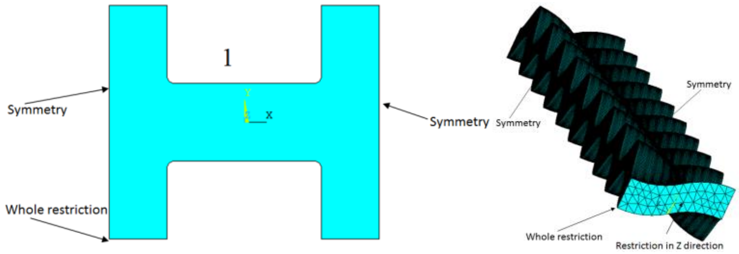

Figure 5: Displacement restrictions for the stress analysis

After the mesh independence study, global size 0.05 is selected for all the designs in the 2D study. The difference between global size=0.05 and size below 0.05 is lower than 1 %. The difference between 190099 elements and 624946 elements is below 2 %, so that 190099 elements is used in 3D model.

The Von mises stress and the first principal stress are obtained by solving the thermal-elasticity mechanics equations in ANSYS. A similar model of a plate-fin heat exchanger is simulated for validation. The same boundary conditions are adopted according to the reference (Sun and Liu, 2007), which concluded that the von mises stress in the fin along a certain path can be calculated by empirical equation (1). In this equation, σ_{max} is the maximum stress of the fin, P is the pressure load on the flow channels, m is the gap between fins and t_f is the thickness of the fins.

$$\sigma_{max} = P\left(0.0283 + 0.6687\frac{m}{t_f}\right) \tag{1}$$

Compared to the correlations, the maximum simulation deviation is less than 4%. The good agreement can validate the reliability of computation model and numerical codes.

3. Results and discussions

Figure 6 shows the temperature distribution of all the designs. It is obvious that the temperature differences in all 2D models are small although the fluid temperature difference is large. The 2nd design has larger temperature difference than the 1st design because the gap between two tunnels is larger. The temperature distribution of primary surface plate is different from the plate-fin designs and the 4th design has larger temperature difference than the 3rd one. The temperature difference of solid plate can be adjusted by adopted different flow tunnel arrangements, which will influence the distribution of thermal stress.

From Figure 7, it indicates that the 1st design has the maximum thermal stress. Although the 4th design has large temperature difference than the 3rd design, the maximum thermal stress is lower than the 3rd design. The maximum thermal stress in the 1st and 2nd designs locate in the connection regions made by traditional manufacturing method, as displayed by dotted line in the Figure 7. If the strength of the bonding joints is weaker than the fin materials, it's recommended to move the bonding joints to the middle of the fins, and this will protect the connection regions from stress concentration. From all the pictures, the maximum thermal stress is observed locates in the corner of the plates. In the plate design, a smooth transition and keeping the connection regions away from the corners are efficient methods to decrease the stress level.

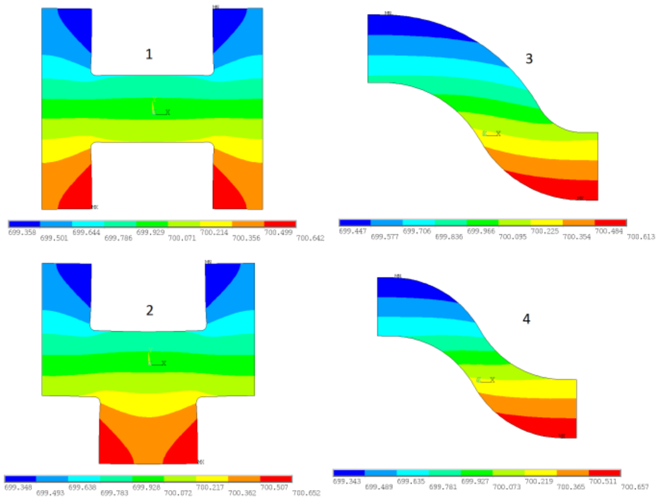

Figure 6: Temperature distributions in different designs/K

Due to the compression strength is much larger than the tensile strength for ceramics, it's better to keep the plate in compression state in the design of ceramic heat exchangers. The first principal stress is always used to evaluate the reliability of brittle materials that always being destroyed in the form of fracture (Schulte-Fischedick et al., 2007). Figure 8 shows that the first principal stress of primary surface plates is larger than the plate fin designs and the outer surface of the primary surface plates owning the maximum tensile stress. The transitional point of the primary surface plate is in tension and the inner surface has low tensile stress relatively.

In 3D study, due to the periodic waveform changes, a more accurate result is obtained. The stress distribution in Figure 7 is similar to the cross section area of 3D model in Figure 9. The maximum stress locates in the connection regions of bubbles. The top surfaces of the offset bubbles primary surface plate have low stress.

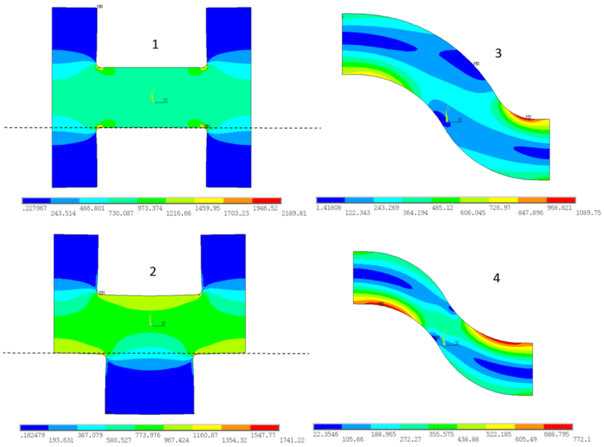

Figure 7 Von mises stress distribution in different designs/MPa

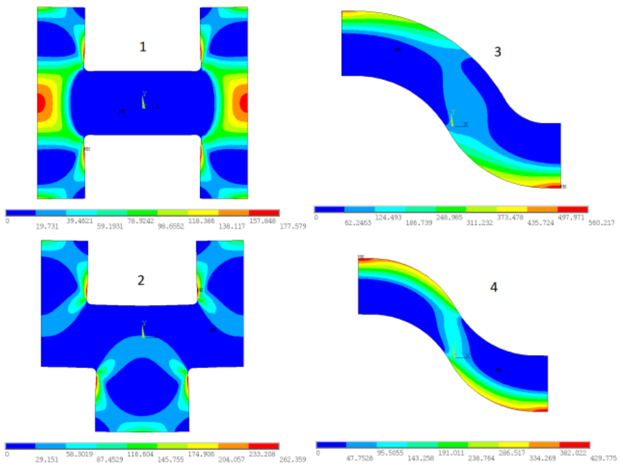

Figure 8 The first principal stress distribution in different designs/MPa

Figure 10 shows that the outer surface of the offset bubbles plate is in tension and possesses the maximum tensile stress as that in Figure 8. The inner surface of the bubbles plate is in compression, so the cracks are predicted to generate and grow initially in the top surface. The transitional point of two adjacent bubbles of the plate is also in tensile stress.

4. Conclusions

After comparison of temperature and thermal stress distribution results, the following conclusions can be drawn: (1) The maximum thermal stress locates in the corners of heat transfer core and it is in the connection regions of common plate-fin designs, so it is recommended to create a smooth transition and keep the connection regions away from the corners to decrease the thermal stress. (2) The transitional point of the primary surface plates is in tension and the inner surface has low tensile stress relatively. (3) In offset bubbles primary surface plate, the maximum stress locates in the connection regions of bubbles. (4) The outer surface of the primary surface plate and offset bubbles plate has the maximum tensile tress, and the cracks will generate initially here.

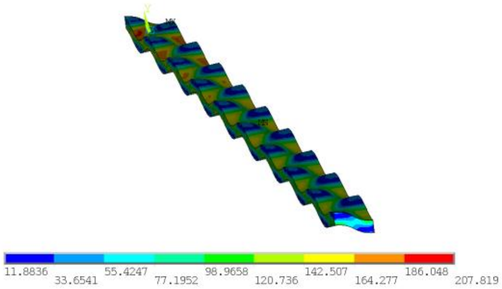

Figure 9 The Von mises stress distribution in offset bubbles primary surface plate/MPa

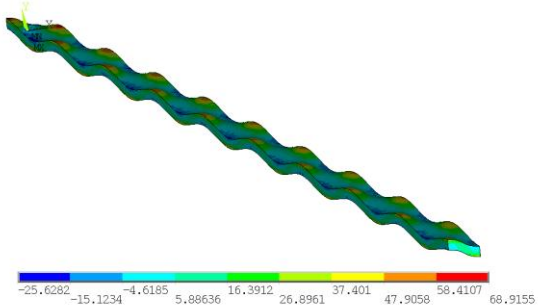

Figure 10 The first principal stress distribution in offset bubbles primary surface plate/MPa

Acknowledgements

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References

McDonald, C. F., Rodges, C., 2005, Ceramic recuperator and turbine---the key to achiving a 40 percent efficient microturbine, Proceeding of the ASME Turbo Expo 2005, 1:963-971

Sommers A., Wang Q., Han X., T'Joen C., Jacobi Y., 2010, Ceramics and ceramic matrix composites for heat exchangers in advanced thermal systems-a review, Appl. Therm. Eng., 30(11-12):1277-1291

Ponyavin V., Chen Y., Cutts J., Wilson M., Hechanova A. E., 2008, Calculation of fluid flow distribution inside a compact ceramic high temperature heat exchanger and chemical decomposer, J. Fluid. Eng-T ASME., 130(6):1-8

Kee R. J., Almand B. B., Blasi J. M., Rosen B. L., Hartmann M., Sullivan N. P., Zhu H., Manerbino A. R., Menzer s., Coors W. G., Martin J. L., 2011, The design, fabrication, and evaluation of a ceramic counter-flow microchannel heat exchanger, Appl. Therm. Eng., 31(11-12):2004-2012

Alm B., Imke U., Knitter R., Schygulla U., Zimmermann S., 2007, Testing and simulation of ceramic micro heat exchangers, Chem. Eng. J., 135(1):S179-S184

Schulte-Fischedick J., Dreiβigacker V., Tamme R., 2007, An innovative ceramic high temperature plate-fin heat exchanger for EFCC processes, Appl. Therm. Eng., 27(8-9):1285-1294

Islamoglu Y., 2004, Numerical analysis of the influence of a circular fin with different profiles on the thermal characteristics in a ceramic tube of heat transfer equipment, Int. J. Pres. Ves. Pip., 81(7):583-587

Sun A., Liu M., Dong Q., 2007, Simulation of plate-fin structure of heat exchanger and modification of strength rules, Machine Design and Research, 23(3):118-120(in Chinese)