CHEMICAL ENGINEERING TRANSACTIONS Volume 25, 2011
Editors Jiří Jaromír Klemeš, Petar Sabev Varbanov, Hon Loong Lam
Copyright © 2011, AIDIC Servizi S.r.l., ISBN 978-88-95608-16-7 ISSN 1974-9791
DOI: 10.3303/CET1125059

Study on Reliability of High Temperature Heat Exchangers

Ting Ma, Linxiu Du, Dongjie Zhang, Yanpeng Ji, Min Zeng, Qiuwang Wang*

Key Laboratory of Thermal Science and Engineering of MOE,
Xi'an Jiaotong University, Xi'an, 710049, China
wangqw@mail.xjtu.edu.cn

Compact high temperature heat exchangers are urgently needed in many highly efficient power and propulsion systems. The big thermal stress and creep deformation under high temperature and high pressure conditions are very serious. In this study, our recent contributions on the reliability analysis of CW primary surface recuperators and bayonet tube high temperature heat exchangers are introduced. The reliability of several compact enhanced heat transfer designs including internally finned bayonet tube, internally and externally finned bayonet tube, and cross wavy (CW) primary surface sheet is investigated. The results indicate that for the bayonet tube, the high stress is caused by high temperature, while for the thin CW primary surface sheet, it is caused by big pressure difference. The creep strain of CW primary surface sheet is also influenced by the big pressure difference. The big thermal stress and creep deformation under high temperature and high pressure conditions are observed. And the big thermal stress and deformation areas of these designs have been found so that the corresponding optimized structures and modified measures have been recommended.

1. Introduction

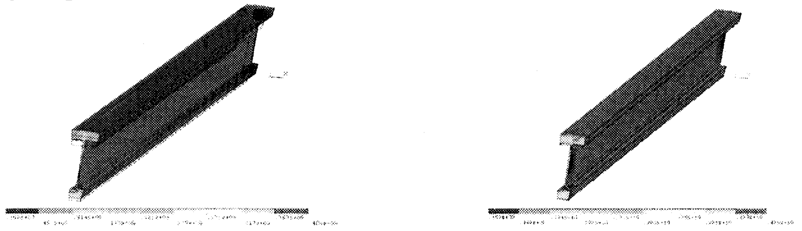
In recent years, different high temperature heat exchangers (HTHEs) are investigated for the microturbine cycle, the hydrogen producing thermochemical cycle, the very high temperature reactor and the externally fired combined cycle. However, current researches focus on the fluid flow and heat transfer performances (Arsenyeva et al. 2009, Picon-Nunez et al. 2007), but few on the reliability of the novel enhanced heat transfer designs. In fact, the big thermal stress and creep deformation under high temperature and high pressure conditions are very serious. Bad deformation in the recuperator may cause the block of the fluid, increase pressure drop and reduce heat transfer performance, or even threaten the safe operation of the whole microturbine system. Tsuda et al. (2010) pointed out that rate-dependent deformation such as visco-plasticity and creep could occur in the plate-fin structures. When the plate-fin structure served at elevated temperature, the unavoidable long-term creep of plate-fin heat exchanger could result in failure (Jiang et al., 2008). The most sensitive component was the joint and its strength was a function of many factors including brazing temperature, brazed residual stress, filler metal thickness, creep properties, etc. Therefore, the validation of safety is the

Please cite this article as: Ma T., Du L., Zhang D., Ji Y., Zeng M. and Wang Q., 2011, Study on reliability of high temperature heat exchangers, Chemical Engineering Transactions, 25, 351-356
DOI: 10.3303/CET1125059

precondition before the novel enhanced heat transfer designs are adopted. In this study, we would like to introduce our recent contributions on the reliability analysis of CW primary surface recuperators and bayonet tube HTHEs by the group of Novel Heat Transfer Technologies and Compact Heat Exchanger (NHTT-CHEX) of Xi'an Jiaotong University.

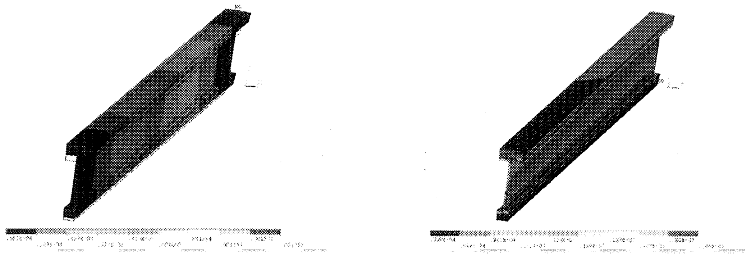
2. Stress analysis of internally finned bayonet tube

The stress of internally finned bayonet tube is numerically investigated by software ANSYS (Ma et al., 2010). Figure 1(a) shows the stress distribution of the novel internally finned bayonet tube. The stress of 99% nodes are less than 250MPa, which is less than the yield stress limit ($\sigma_{0.2}$=398 MPa) of Inconel 625. The big stress exists in the joint of inner fins and inner tubes, so the welding quality of the joint must be ensured. The stress of a few nodes near the end joint of fin and inner tube exceeds the yield limit due to the constraints at this location. However, in the real heat exchanger, the inner fins are far from the end of inner tube so that the stress can be reduced. As shown in Fig.2(a), the maximum deformation of the internally finned bayonet tube is 1.762 mm. The expansion is very obvious and mainly occurs in the *Y* direction. This is produced by the big temperature difference between the inner tube and outer tube.



(a) Stress of finned bayonet tube *(b) Stress of traditional finned tube*

Fig.1 Comparison of von mises stress (Pa)



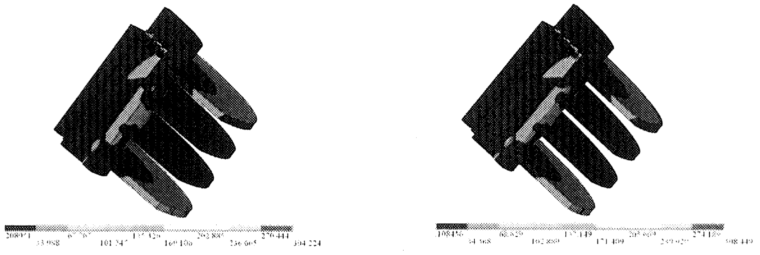
(a) Deformation of finned bayonet tube *(b) Deformation of traditional finned tube*

Fig.2 Comparison of deformation (m)

In order to verify the advantage of bayonet structure, the stress and deformation of traditional finned tube are investigated, as shown in Fig.1(b) and Fig.2(b). For the traditional finned tube, the displacement of both ends of inner and outer tubes is restricted in the *Z* direction. It can be seen that the even the minimum stress exceeds the yield stress limit of Inconel 625. However, the maximum displacement of finned bayonet tube is larger than that of traditional finned tube because its one end can expand freely. Therefore, the bayonet structure is superior to the traditional tube for use in the high temperature heat exchanger.

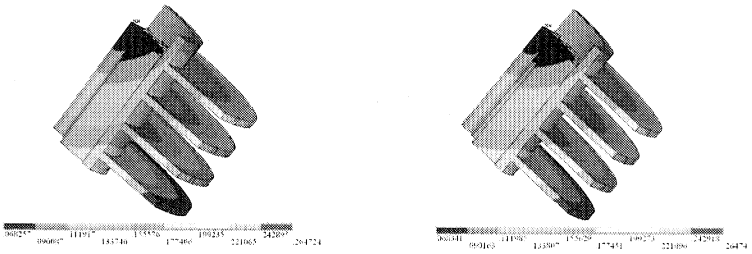
3. Stress analysis of internally and externally finned bayonet tube

The stress characteristic of internally and externally finned tube is investigated by Ji et al. (2010). As shown in Fig.3, the stress distributions of the internally and externally finned bayonet tube with and without pressure loads on both sides are similar. The maximum von mises stress occurs at the joint between inner fins and tubes. The maximum stress is 304.223 MPa and 308.449 MPa, respectively. The stresses are less than the yield stress limit of Inconel 625. The maximum stress of the case with pressure loads is a little bigger than that of the case without pressure loads. So the pressure is not the main factor to cause high stress. It can be concluded that the expansion results from the high temperature rather than the pressure difference for the internally and externally finned bayonet tube. As shown in Fig.4, the expansion mainly occurs at the edge of outer fins because the temperature in this place is the biggest and there are no constraints. Therefore, the tube pitch should be designed a little larger than that of traditional heat exchangers that used for low temperature conditions.



(a) Stress without pressure loads *(b) Stress with pressure loads*

Fig. 3 Von mises stress of internally and externally finned tube (MPa)



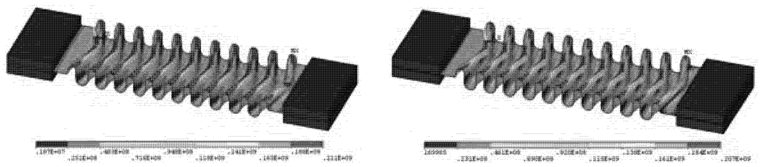
(a) Deformation without pressure load *(b) Deformation with pressure load*

Fig. 4 Deformation of internally and externally finned tube (mm)

4. Stress analysis of CW primary surface sheet

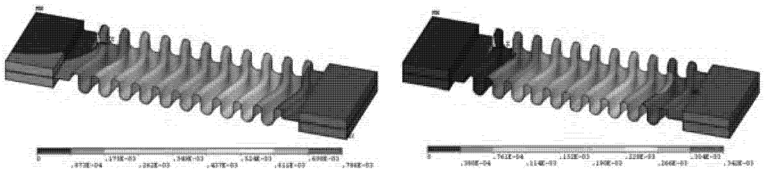
The stress of CW primary surface sheet under high temperature is analyzed with APDL language in ANSYS by Zhang et al. (2008a). The von mises stress distributions with and without temperature load are shown in Fig.5. The maximum stress of the case without temperature load is 207 MPa, which is almost the same as that of the case with temperature load. Therefore, the pressure difference is the main reason to cause high stress. High stress occurs in the areas near the top points of air passages because they have to endure the pressure difference between the air side and gas side and the expansion is restricted by the nearby sheet.

Figure 6 shows the deformation distributions of the CW primary surface sheet. The maximum deformation of the case with temperature load is 0.778 mm in the X direction, 0.00529 mm in the Y direction and 0.106 mm in the Z direction. The displacement vector sum is 0.786 mm, which is 2.3 times the deformation of the case without temperature load. The comparison shows that the expansion results from the high temperature. The expansion mainly occurs in the X direction and the expanded length of one period is 0.0778 mm. Hence, it is recommended that over tightly assembly should be effectively avoided for the proper assembly of recuperators.



(a) Stress with temperature load *(b) Stress without temperature load*

Fig.5 Von mises stress of CW primary surface sheet (Pa)



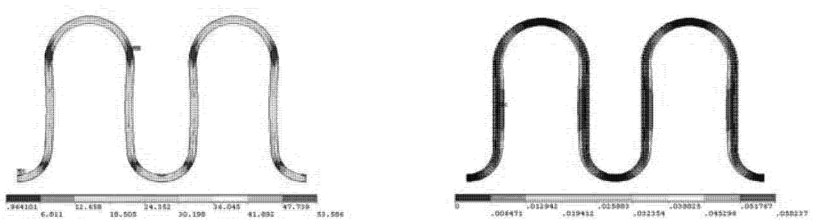
(a) Deformation with temperature load *(b) Deformation without temperature load*

Fig.6 Deformation of CW primary surface sheet (m)

5. Creep analysis of CW primary surface sheet

The stress and creep strain of CW primary surface sheet operating for 40000 h are analyzed by Zhang et al. (2008b). Creep of recuperator occurs mostly in the steady creep step because it works continuously under high temperature. The implicit Norton creep equation is applied. The von mises stress and creep deformation distributions of the recuperator operating for 40000 h are shown in Fig.7. It can be seen that the maximum von mises stress occurs at the bottom of air passage and the maximum value is 53.38 MPa which is much less than the creep rupture strength of Alloy 347 (108 MPa) under 621ºC and 10^5 operating hours (Xu, 2000). Hence, Alloy 347 has enough creep-resistant performance to manufacture recuperator. The maximum deformation occurs at the middle part of the passages, which makes the air passages expand and the gas passages contract. The reason is that the thermal stress caused by hot gas decays rapidly with the increase of time and the stress caused by the air-side high pressure is the dominant factor to influence the creep strain.

The effect of thickness of the sheet on von mises stress and creep deformation is investigated, as shown in Fig.8. It can be seen that the von mises stress significantly decreases with the increase of thickness. The creep deformation decreases rapidly when the thickness is less than 0.12 mm. However, it changes slightly when the thickness is more than 0.12 mm. Considering the thermal resistance and weight, 0.12 mm may be the maximum thickness for the recuperator in the view of stress and creep performances.



(a) Von mises stress field (MPa) *(b) Creep deformation distribution (mm)*

Fig. 7 Von mises stress and creep deformation distribution (40000 h)

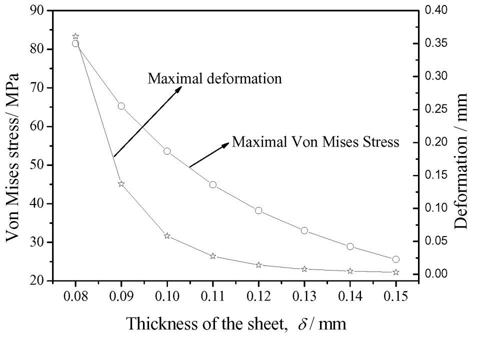


Fig. 8 Von mises stress and creep deformation distribution vs. thickness

6. Conclusions

In the present study, the reliability of several compact enhanced heat transfer designs including internally finned bayonet tube, internally and externally finned bayonet tube, and CW primary surface sheet is investigated. The results indicate that for the bayonet tube, the high stress is caused by high temperature, while for the thin CW primary surface sheet, it is caused by big pressure difference. The creep strain of CW primary surface sheet is also influenced by the big pressure difference. According to the analysis, many optimized structures and modified measures are recommended. For the shell-and-tube heat exchangers, bayonet structure is superior to the traditional tube for use in the high temperature heat exchanger, and the tube pitch should be designed a little larger than that of traditional heat exchangers that used for low temperature conditions. For the CW primary surface sheet, over tightly assembly should be effectively avoided for the proper assembly of recuperator. However, the mutual effects between thermal hydraulic and stress performances have not been taken into consideration. Moreover, the durability and reliability of HTHE under high temperature and high pressure conditions should be further tested by experiment. These works should be undertaken in the future.

Acknowledgments

This work was supported by the National High Technology R&D Project of China (No.2007AA050501 and No.2007AA05Z204), the International Cooperation Program of Science and Technology R&D Project of Shaanxi Province (No.2006KW-24) and the Fundamental Research Funds for the Central Universities.

References

Arsenyeva O., Tovazhnyansky L., Kapustenko P. and Khavin G., 2009, Mathematical modelling and optimal design of plate-and-frame heat exchangers, Chemical Engineering Transactions, 18, 791-796.

Ji Y.P., Ma T., Zeng M. and Wang Q.W., 2010, Stress analysis of bayonet tube with inner and outer fins, Proceedings of 16th Chinese Engineering Thermophysics Society Conference 2010, 103472 (In Chinese)

Jiang W., Gong J.M., Chen H. and Tu S.T., 2008, The effect of filler metal thickness on residual stress and creep for stainless-steel plate-fin structure, Int. J. Pres. Ves. Pip., 85:569-574

Ma T., Ji Y.P., Zeng M. and Wang Q.W., 2010, Numerical research on high temperature stress characteristic of internally finned bayonet tube, Proceedings of 16th Chinese Engineering Thermophysics Society Conference 2010, 103468 (In Chinese)

Picon-Nunez M., Canizalez-Davalos L. and Morales-Fuentes A., 2007, Alternative Design Approach for Spiral Plate Heat Exchangers, Chemical Engineering Transactions, 12, 183-188.

Tsuda M., Takemura E., Asada T., Ohno N. and Igari T., 2010, Homogenized elastic-viscoplastic behavior of plate-fin structures at high temperatures: Numerical analysis and macroscopic constitutive modeling, Int. J. of Mech. Sci., 52(5):648-656

Xu H., 2000, Machine Design Handbook 2 (2nd Edition), China Machine Press, Beijing, 20-30 (in Chinese)

Zhang D.J., Zeng M. and Wang Q.W., 2008a, Three-dimensional stress analysis and configuration optimization of cross wavy primary surface recuperator for microturbine system, Proceedings of the ASME Turbo Expo 2008, 1: 905-910

Zhang D.J., Zeng M., Wang J.W. and Wang Q.W., 2008b, Creep analysis of cross wavy primary surface recuperator for microturbine system, Proceedings of the ASME Turbo Expo 2008, 1: 899-904