Heat transfer and stress analysis for a high temperature heat exchanger with inner and outer fins

Ting Ma, Ming Zeng and Qiu-wang Wang*

School of Energy and Power Engineering
Xi'an Jiaotong University
Xi'an, Shaanxi, 710049, P.R. China
http://chex.xjtu.edu.cn

March 27, 2012
Who Am I?

Qiu-Wang Wang √

Qui-Wang Wang ×

King

王

秋

旺

Autumn

Vigorous
Where Am I From?

A = Xi’an
B = Beijing
C = Zurich
D = Budapest
E = Veszprémen
OUTLINE

1. Introduction
2. HXs with Inner/Outer Fins
3. Optimization of Heat Transfer & Thermal Stress
4. High Temperature Heat Transfer Mechanism
5. Conclusions and Discussion
6. Acknowledgements
1. Introduction

Applications of High Temperature Heat Exchangers (HTHEs)

- Sulfur-iodine thermochemical cycle
- Hydrogen production S–I thermochemical cycle
- High Temperature gas cooled Reactor
- Recuperative microturbine system
- Externally Fired Combined Cycle
- Solar energy system
- Solid Oxide Fuel Cell
Eg.1: Microturbine system with recuperative cycle and EFGT cycle

- System’s electricity efficiency may be improved up to 30% with a recuperator.
- Gas turbines: strict requirements for the cleanliness of flue gas (erosion, incrustation, and corrosion).

HTHE is one of the crucial elements.
Eg. 2: Very high temperature reactor (VHTR) and hydrogen production

---HTHE is one of crucial elements for use!

\[
\begin{align*}
\text{VHTR intermediate heat exchanger (IHX)} & \quad T_{\text{max}} = 950^\circ\text{C} \\
\text{S-I thermochemical hydrogen production} & \quad \varepsilon_{\text{max}} = 95\%
\end{align*}
\]
1. Introduction

**Developing trends of HTHE**

- Higher Temperature, Higher Pressure
  - e.g. Recuperator for microturbine system >650°C
  - Hydrogen production >850°C
  - IV generation high temperature gas-cooled reactors >900°C
  - Solid oxide fuel cells >1000°C
  - Externally fired gas turbine cycle >1000°C

**Chemical, Metallurgical, Glass and Waste (C. Luzzatto et al)**

- Maximum temperature: 1500°C
- Maximum pressure: 2.5 MPa
- Maximum differential pressure: 0.6 MPa

1. Introduction

What should we do for HTHEs?

- More compact heat transfer structure to improve efficiency and save cost

Very expensive superalloy and ceramic

Plate-fin heat exchanger

University of California, Berkeley
University of Nevada
German Aerospace Center
Idaho National Laboratory
Ohio State University
1. Introduction

What should we do for HTHEs?

- More reliable heat transfer structure to improve safety

Bayonet tube heat exchanger

High temperature creep and deformation
OUTLINE

1. Introduction
2. HXs with Inner/Outer Fins
3. Optimization of Heat Transfer & Thermal Stress
4. High Temperature Heat Transfer Mechanism
5. Conclusions and Discussion
6. Acknowledgements
2. HXs with Inner/Outer Fins

**Background**

*Heat Transfer Enhancement for Gas (Convective)*

- Fin-and-tube (tube-fin) heat exchangers are encountered in many power engineering, chemical applications such as compressor inter-coolers, air-coolers and fan coils
- Fins are usually used on gas-side to enlarge the heat exchanger surface and hasten the disturbance of the flow
- Gas-liquid: outside fin and tube HEX (as usual)
2. HXs with Inner/Outer Fins

HXs with Inner Fins

- Increasing the gas velocity to enhance heat transfer (compressed air – cooling water)
2. HXs with Inner/Outer Fins

Compressor intercooler

One-end Blocked inserted tube
2. HXs with Inner/Outer Fins

--- Major Concerns

I. The Effect of Center Tube (Diameter)?
II. The Effect of Longitudinal Fin Profiles?
III. The Effect of Fin Cross-Section Profiles?
IV. How to Evaluate Comprehensive Performance?
2. HXs with Inner/Outer Fins

Effect of **Blocked Core-Tube Diameter**

**Beneficial Coefficient**

\[
\beta = \frac{\Phi \cdot m}{\Delta p \cdot A}
\]

---

**Diagram:**
- Variables: \( D_o \), \( D_i \), \( d_o \), \( d_i \)
- Core-tube and out-tube highlighted.

---

**Notes:**
- Benefit: \( \Phi \cdot m \)
- Cost: \( \Delta p \cdot A \)
2. HXs with Inner/Outer Fins

Effect of Blocked Core-Tube Diameter

Velocity field and temperature field at different ratio under identical moderate pressure drop (not to scale)

(a) velocity field at z=0.31m

(b) temperature field at z=0.31m
2. HXs with Inner/Outer Fins

Effect of Blocked Core-Tube Diameter

- **uniform wall temp** (identical mass flow rate)
- **constant wall heat flux** (identical mass flow rate)

- Optimal ratio 0.5 to 0.625
- not sensitive to wave numbers (>10)

2. HXs with Inner/Outer Fins

Effect of Fin Longitudinal Profiles

(a) interrupted wavy fin,
(b) sinusoidal wavy fin,
(c) plain fin

Velocity distributions at different streamwise locations (Re=2713)
2. HXs with Inner/Outer Fins

Effect of Fin Longitudinal Profiles

Comparisons of Nusselt number and $j/j_p$ with Reynolds number

Enhanced heat transfer performance based on the area goodness factor

2. HXs with Inner/Outer Fins

Effect of Fin Cross-Section Profiles
Choose the tube with V-shaped fin profiles to be the base tube for comparisons.

**Identical mass flow rate:**
\[
\left( \frac{A_c \text{Re}}{D_h} \right)_{s\ or\ z} = \left( \frac{A_c \text{Re}}{D_h} \right)_{v}
\]

**Identical pumping power:**
\[
\left( \frac{A_c \text{Re}^3}{D_h^4} \right)_{s\ or\ z} = \left( \frac{A_c \text{Re}^3}{D_h^4} \right)_{v}
\]

**Identical pressure drop:**
\[
\left( \frac{f \text{Re}^2}{D_h^3} \right)_{s\ or\ z} = \left( \frac{f \text{Re}^2}{D_h^3} \right)_{v}
\]

\[
\Phi_{s\ or\ z} = \frac{(\text{NuA}_h/D_h)_{s\ or\ z}}{(\text{NuA}_h/D_h)_v}
\]

\[
\Phi_v = \frac{(\text{NuA}_h/D_h)_v}{(\text{NuA}_h/D_h)_v}
\]
Friction factors and Nusselt numbers

S-shaped: \( \text{Nu} = 0.113Re^{0.567}, \text{f} = 3.39Re^{-0.579} \)

Z-shaped: \( \text{Nu} = 0.09Re^{0.601}, \text{f} = 1.82Re^{-0.524} \)

V-shaped: \( \text{Nu} = 0.077Re^{0.598}, \text{f} = 1.9Re^{-0.533} \)
2. HXs with Inner/Outer Fins

Effect of Fin Cross-Section Profiles

- Identical pumping power
- Identical mass flow rate
- Identical pressure drop

Z-shape is the best

2. HXs with Inner/Outer Fins

Summary

\[ \beta = \frac{\Phi \cdot m}{\Delta p \cdot A} \]

\[ \Phi_{s \text{ or } z} = \frac{(\text{NuA}_h / D_h)_{s \text{ or } z}}{(\text{NuA}_h / D_h)_v} \]

\[ (j / j_p) / (f / f_p) \]
2. HXs with Inner/Outer Fins

Bayonet Tube HTHE with Inner and Outer Fins

Internally finned tube

Externally finned tube

Tube with inner and outer fins

Used for gas-gas HTHE?
Advantages of novel bayonet tube HTHE with inner and outer fins:

- Fins are welded outside and inside outer tubes
- Combination of superalloys and stainless steels
2. HXs with Inner/Outer Fins

Bayonet Tube HTHE with Inner and Outer Fins

- Fins are employed outside and inside outer tubes of bayonet-elements
- 2<sup>nd</sup> zone: high temperature zone, made of nickel-based superalloys
- 3<sup>rd</sup> zone: low temperature zone, made of stainless steel
2. HXs with Inner/Outer Fins

**Thermal Design**

**Segmented LMTD method --- Improved from the traditional Log-Mean Temperature Difference (LMTD) method:**

- Divide the whole HTHE into several blocks along the tube length direction.
  - block: the space between adjacent baffles.
- Consider every block to be a small HTHE and use LMTD method in every block.
OUTLINE

1. Introduction
2. HXs with Inner/Outer Fins
3. Optimization of Heat Transfer & Thermal Stress
4. High Temperature Heat Transfer Mechanism
5. Conclusions and Discussion
6. Acknowledgements
3. Optimization of Heat Transfer & Thermal Stress

3.1 Heat Transfer Analysis by CFD (Channel)

Physical model

- To assist structure design before experiment, pressure drop and heat transfer performances of the inside of bayonet element are investigated by CFD.
- Realizable $k-\varepsilon$ model with standard wall function, SIMPLEC algorithm, Power-Law Differencing Scheme.
3. Optimization of Heat Transfer & Thermal Stress

3.1 Heat Transfer Analysis by CFD (Channel)

Different Fluid Flow Patterns

Case (a) Inner In-Annular Out
Temperature Rise: 66 °C

Case (b) Annular In-Inner Out
Temperature Rise: 58 °C

Temperature distributions comparison (°C)

◆ Heat transfer rate is almost the same.
◆ There exists a significant temperature difference between outer tube and inner tube.
3. Optimization of Heat Transfer & Thermal Stress

3.1 Heat Transfer Analysis by CFD (Channel)

Different Fluid Flow Patterns

Case (a) Inner In-Annular Out
Pressure Drop: 635 Pa

Case (b) Annular In-Inner Out
Pressure Drop: 3250 Pa

Pressure distributions comparison

◆ Pressure drop for case (b) is much higher than that of case (a).
◆ Air is recommended to flow in the inside of the inner tube at first and then flow along the annular space.
3. Optimization of Heat Transfer & Thermal Stress

3.1 Heat Transfer Analysis by CFD (Channel)

Temperature rise and heat transfer rate vs. gap

- Temperature rise and heat transfer rate are almost the same as that of the baseline design when the gap is less than 1 mm.
- During structure design, the gap is recommended to be less than 1 mm and this gap has no effect on the heat transfer performance.
- The effect of gap on thermal stress should be further studied!
3. Optimization of Heat Transfer & Thermal Stress

3.2 Thermal Stress Analysis (Channel)

Von mises stress distribution vs. structure

- Von mises stress of traditional tube structure is much higher than that of present bayonet tube structure.
- The reason is that both sides of traditional tube are restricted by tube sheets, while only one side of bayonet tube is restricted.
3. Optimization of Heat Transfer & Thermal Stress

3.2 Thermal Stress Analysis (Channel)

Von mises stress distribution vs. gap

- When there exists a narrow gap, the von mises stress is greatly reduced.
- There should be a narrow gap between the inner fin and inner tube surface.
3. Optimization of Heat Transfer & Thermal Stress

3.2 Thermal Stress Analysis (Channel)

**Influence of gap**

- Stress comparison
- Heat transfer comparison

- It is recommended that the inner fin and inner tube should not be welded together and the gap between them should be less than 1 mm according to the coupled consideration of heat transfer and stress performances.
3. Optimization of Heat Transfer & Thermal Stress

3.2 Thermal Stress Analysis (Channel)

Influence of cross section geometry

The Z type is superior than the S type and V type finned tube in the stress resistance.

Z type
Max Stress: 26.9MPa

S type
Max Stress: 35.9MPa

V type
Max Stress: 33.3MPa
3. Optimization of Heat Transfer & Thermal Stress

3.2 Thermal Stress Analysis (Channel)

Influence of pressure loads

- Junction between inner tube and inner fin produce high stress.
- Temperature difference is the main reason to cause high stress, but pressure difference has little effect.
The expansion comes from the high temperature.

The maximum deformation occurs on the outside edge of outer fins.
3. Optimization of Heat Transfer & Thermal Stress

3.3 Fluid Flow Distribution Analysis (HTHE system)

- Crude flow maldistribution
- Large model with huge amounts of fins

Additional study!
Simplified model!
Derivation process of Permeability and Inertial resistance factor:

**Source term of momentum equation:**

\[ S_i = \frac{dp}{dx_i} = \mu \frac{\partial}{\partial x} \vec{v}_i + c'_2 \frac{1}{2} \rho |\vec{v}_i| \vec{v}_i \]

\[ \vec{v}_i = \frac{\vec{v}_D}{\phi} \]

**Formulas of Plain finned tubes:**

\[ \Delta p = f \cdot \frac{1}{2} \rho \left( \frac{\vec{v}_D}{\sigma} \right)^2 \frac{1}{d_h} \]

\[ f = \frac{c_1}{Re} + c_2 \]

\[ Re = \frac{\rho (|\vec{v}_D| / \sigma) d_h}{\mu} \]

\[ \hat{\sigma} = \frac{d_h^2 \cdot \sigma}{c_1 / 2 \cdot \phi} \]

\[ c'_2 = \frac{\phi^2 \cdot c_2}{\sigma^2 \cdot d_h} \]
3.3 Fluid Flow Distribution Analysis (HTHE system)

Validation of macro-performance

Validation of plain finned tubes in a straight channel (2D)

Maximum deviation: 19%
Average deviation: 11%
3. Optimization of Heat Transfer & Thermal Stress

3.3 Fluid Flow Distribution Analysis (HTHE system)

Validation of micro-performance

3D and 2D models with 18 channels for validation
3. Optimization of Heat Transfer & Thermal Stress

3.3 Fluid Flow Distribution Analysis (HTHE system)

Validation of micro-performance

- Fluid flow distributions are very similar
- Total pressure drop: 3D (12.6 kPa), 2D (11.3 kPa)
- Nodes number: 3D (4.859 million), 2D (0.067 million)

---

Reliability of numerical method

Superiority in engineering applications
3. Optimization of Heat Transfer & Thermal Stress

Velocity distributions ($Re=77792$)

(a) Case A
(b) Case B
(c) Case C
(d) Case D

Base Line Design
3. Optimization of Heat Transfer & Thermal Stress

Mass flow distributions of 2# channels (Re=77792)

(a) Case A
(b) Case B
(c) Case C
(d) Case D
3. Optimization of Heat Transfer & Thermal Stress

Average nonuniformity of mass flow rate:

\[ S = \sqrt{\frac{\sum_{i=1}^{N} (q_{m,i} - \bar{q}_m)^2}{\bar{q}_m}} / (N - 1) \]

- Case C and D is superior to other cases, especially in the high inlet Reynolds number conditions (velocity non-uniformity).
- The pressure drop is too high that the Case D is unsuitable.
- Compared with the Case A, the nonuniformity of Case C can be reduced by 42% while the pressure drop is almost the same in the base line condition.
3. Optimization of Heat Transfer & Thermal Stress

3.4 Thermal Stress Analysis (HTHE system)

Influence of heat-insulating material on pass-partition surfaces

- Large temperature difference exists in the pass-partition.
- Heat-insulating material is important to reduce thermal stress.

Von mises stress with heat-insulating material (MPa)

Von mises stress without heat-insulating material (MPa)
3. Optimization of Heat Transfer & Thermal Stress

3.4 Thermal Stress Analysis (HTHE system)

Influence of fillet in shell corner

◆ Large stress exists in the corner due to discontinuous geometry.
◆ Fillet is important to reduce thermal stress in shell corner.
OUTLINE

1. Introduction
2. HXs with Inner/Outer Fins
3. Optimization of Heat Transfer & Thermal Stress
4. High Temperature Heat Transfer Mechanism
5. Conclusions and Discussion
6. Acknowledgements
4. High Temperature Heat Transfer Mechanism

4.1 Characteristics of High Temperature Heat Transfer

Local velocity and Reynolds number along stream-wise direction

As heated from 850 K to 1250 K, velocity is increased by 50%, Reynolds number is reduced by 25% due to the variation of gas physical properties.

Heat transfer and fluid flow in HTHE can’t become periodical, which is different from the traditional low temperature heat exchanger.
Validation of numerical method

- Reynolds stress turbulent model (RSM) with Enhanced wall treatment, SIMPLE algorithm, Second Upwind Scheme.
- Very fine meshes with $y^+ < 2$ at the wall adjacent cell are constructed and 12 cells are established within the viscosity-affected near-wall region where Reynolds number is less than 200.

Velocity profile validation

Heat transfer validation
4. High Temperature Heat Transfer Mechanism

Effects of rib height and temperature on flow profile

(a) $H=1\ mm,\ T=850\ K$

(b) $H=1\ mm,\ T=1250\ K$

(c) $H=0.5\ mm,\ T=1250\ K$

(d) $H=2\ mm,\ T=1250\ K$

- Inlet temperature has little effect on basic structure of fluid flow. But the velocity value is enhanced so that heat transfer is improved.
- Increasing rib height can improve heat transfer by increasing fluid disturbance.
4. High Temperature Heat Transfer Mechanism

Effects of temperature on $Nu$ and $f$

Heat transfer and pressure drop comparisons of channel with $h=1$ mm rib at different temperatures

- For the same geometrical structure, trends of $Nu$ and $f$ deviate from real variation trends of heat transfer and pressure drop at different temperatures.
- $Nu$ and $f$ are unsuitable to compare the heat transfer and pressure drop performances among different temperature conditions because the physical properties of fluid change with temperature variation.
**Heat transfer and pressure drop comparisons of channels with different rib heights at different temperatures**

- Effects of inlet temperature and rib height on the heat transfer and pressure drop performances are different.
- Compared to increasing the **rib height**, more heat can be transferred by increasing the **inlet temperature** accompanied with less pressure drop.
High pressure drop is more serious as inlet temperature increases, which is a significant problem to restrict compact heat transfer structure for HTHE.

It is proposed to use the highly compact heat transfer structure (such as high rib) at the low temperature region and replace it by relatively loose heat transfer structure (such as low rib) at the high temperature region.
4. High Temperature Heat Transfer Mechanism

4.2 High Temperature Experiment

Baffles for guiding fluid flow
Two gas flow paths.

The air of tube side comes from the compressor.

The air of shell side is provided by the fan. As the air flows into the combustion chamber, it burns with the fuel and the high temperature air-fuel mixture is produced.
4. High Temperature Heat Transfer Mechanism

High Temperature Experimental System

Heat transfer and pressure drop performances test
**4. High Temperature Heat Transfer Mechanism**

**High Temperature Experimental Results**

Heat transfer effectiveness comparison

- The novel HTHE can improve the overall heat transfer performance.
- Internal fluid flow distribution optimization and compactness increment can improve the heat transfer performance.

OUTLINE

1. Introduction
2. HXs with Inner/Outer Fins
3. Optimization of Heat Transfer & Thermal Stress
4. High Temperature Heat Transfer Mechanism
5. Conclusions and Discussion
6. Acknowledgements
5. Conclusions and Discussion

- A novel bayonet tube HTHE with inner and outer fins is proposed for high temperature applications.
- The heat transfer channels and system are studied and optimized by CFD method and Computational Mechanics.
- Experimental results indicate that the efficiency of optimized HTHE is higher than the original one and published HTHEs.
- Mechanism of high temperature heat transfer is recognized by CFD method.
5. Conclusions and Discussion

**Challenges of CAPE for HTHE**

- Separation method of total heat transfer coefficient for gas-gas HTHE.
- Data sharing and transfer methods for multi-scale model.
- Porous media model for HTHE system.

**Challenge-1**: Multi-Scale Analysis for HTHE
5. Conclusions and Discussion

Challenges of CAPE for HTHE

Challenge-2: Multi-Physical Fields Coupling Analysis for HTHE

- Grid establishment method for multi-physical fields interaction process.
- Data sharing and transfer methods between multi-physical fields.
- Optimization method for multi-physical fields coupling analysis coupled with Intelligence Algorithm.
5. Conclusions and Discussion

Selected References

Papers


Patents

- Q.W. Wang, T.Ma, Q.Y. Chen, Internal and external fins intubations type high temperature heat exchanger, Chinese Patent: ZL200810150820.3, 2010-07-21

This work is supported by:

- **National High Technology R&D Project of China (No. 2007AA05Z204)**
- **International Cooperation and Exchanges Project of NSFC (No. 51120165002)**
- **Exchange Scholar Program of University of Nevada, Las Vegas (No. P-1-04954)**
Thank you for your attention!

Welcome Comments!

Dr. Qiuwang Wang, Professor
School of Energy and Power Engineering
Xi'an Jiaotong University
Email: wangqw@mail.xjtu.edu.cn
Tel: +86-29-82668720
http://chex.xjtu.edu.cn