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Preliminary Analysis of Airfoil PCHE for the N_2-PCS Recuperator Design

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1. Introduction

Sodium-cooled Fast Reactor (SFR) is one of the Gen-IV reactor project. SFR can reuse spent fuel from pressurized water reactor and burn up minor actinides. Due to such advantages, Russia, Japan, France, India and other counties including South Korea have constructed or planned to build SFR.

The Rankine cycle which is proven technology of power conversion system, uses water as working fluid. However, application of a Rankine cycle to a SFR has a huge risk due to sodium water reaction. A supercritical carbon dioxide Brayton cycle was considered to alternative option for SFR, but sodium-carbon dioxide reaction is also occurred at high temperature [1]. Recently, application of nitrogen Brayton cycle was suggested as power cycle of ASTRID, SFR project of France [2]. Nitrogen does not react with sodium because nitrogen is inert gas. By using N_2-Power Conversion System (N_2-PCS), SFR is free from the risk of sodium-water and sodium-CO_2 reaction.

Printed Circuit Heat Exchanger (PCHE) provides compact size with sufficient heat transfer and has wide working range. Photochemical etching process gives complex channel shape with small size, and diffusion bonding process provides endurance at high temperature and pressure. Brayton cycle is required a high-efficient recuperator which has endurance at high temperature and pressure because its compression ratio is smaller than Rankine cycle. PCHE satisfies requirements for the recuperator. PCHE is considered as heat exchanger of Brayton cycle system for reducing size of heat exchanger. Various channel shapes (zigzag, S-shape fin, airfoil fin) were suggested to obtain high compactness and reduce pressure drop. Airfoil channel PCHE provides very low pressure drop with same heat transfer rate of other complex channel shape PCHEs (zigzag, S-shape) [3]. However, optimized channel shapes and configurations are not clearly defined for various applications.

In this research, design of PCHE for the N_2-PCS recuperator is studied for small size advantage of SFR. Airfoil PCHE designs with various airfoil configurations and mass fluxes are obtained, and these design are compared with a design value of ASTRID.

2. Design code and validation

For design airfoil PCHE, a 1-D PCHE design code is made by using MATLAB. Heat transfer is calculated from heat resistance of convection at both channel and conduction at solid body of PCHE (eqs. 1-2). Heat transfer coefficient of both channel are calculated by the modified Dittus-Boelter correlation for airfoil channel (eqs. 3-5). Pressure drop equation is composed of 2 parts. Pressure drop due to friction is calculated from the modified Blasius correlation (eq. 6). Other part is pressure drop due to thermal acceleration of working fluid (eq. 7). Thermodynamic properties (density, enthalpy, viscosity) are calculated from module which uses NIST REFPROP [4].

$$q_h'' = \left(\frac{1}{h_h A_h} + \frac{1}{R_{th,w}} + \frac{1}{h_c A_c} \right)^{-1} \left(\bar{T}_h - \bar{T}_c \right) \quad (1)$$

$$\frac{1}{R_{th,w}} = 1.241 \zeta_h \zeta_v + 0.441 \quad (2)$$

$$h = \frac{1}{Nu} \frac{D_h}{k} \quad (3)$$

$$Nu_{cooling} = 0.0267 \, \mathrm{Re}^{0.8} \, \mathrm{Pr}^{0.3} \, \zeta_h^{-0.0918} \zeta_v^{-0.0112} \quad (4)$$

$$Nu_{heating} = 0.0275 \, \mathrm{Re}^{0.8} \, \mathrm{Pr}^{0.4} \, \zeta_h^{-0.0918} \zeta_v^{-0.0112} \quad (5)$$

$$f_{Fanning} = 0.0575 \, \mathrm{Re}^{-0.192} \, \zeta_h^{-0.226} \zeta_v^{-0.0311} \quad (6)$$

$$\Delta P = 4 f \frac{l}{D_h} \frac{\rho v^2}{2} + G^2 \left(\frac{1}{\rho_{out}} - \frac{1}{\rho_{in}} \right) \quad (7)$$

The design code initializes temperature of each nodes which are used for calculation of heat transfer. After the initialization, temperature of each nodes are used to obtain material properties. When temperatures of the last node are satisfied pre-calculated temperature of cold channel outlet and hot channel inlet, heat transfer calculation is finished. After the heat transfer calculation process, hot and cold channel temperature profiles of the heat exchanger are used to calculate pressure drop.

For validating a 1-D PCHE design code, CFD analysis is used for checking applicability of previous correlations for airfoil channel with CO_2 to airfoil channel with N_2. Basic structure of the code is reliable, because the code is only depend on energy balance. Consequently, checking applicability of correlation for CO_2 at airfoil channel to N_2 at airfoil channel is more important. CFD analysis is performed at same geometry of CO_2 correlations for airfoil channel [4]. Airfoil channel is composed of NACA 0020 airfoil with 6mm chord length. NACA 0020 airfoil is selected due to consideration for productivity issue of PCHE due to sharp edge of airfoil. In addition, existing correlation for airfoil PCHE is only considered NACA 0020 airfoil [4]. Horizontal and Vertical number are 3.0. From the previous test, mesh dependence of solution was disappeared when test cases have more than 13 million meshes for both fluid sections and solid section [4]. As a result, number of meshes is 13 million for current CFD domain. CFX 16.2 is used to perform CFD analysis. From the previous test, the k-ε turbulence model with wall function and the SST turbulence model without wall function showed similar heat transfer and pressure drop results [4]. Due to limitation of computing power, the k-ε turbulence model with wall function is selected for current research. Fig. 1 is schematic view of CFD domain. Fig. 2 shows boundary conditions and front view of CFD domain.

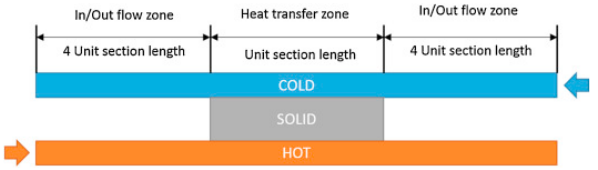

Fig. 1. Schematic view of CFD domain for validation. [4]

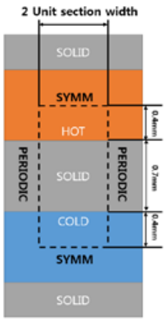

Fig. 2. Boundary conditions of simulation domain. [4]

The Reynolds number and the Fanning friction factor from N_2 CFD analysis are compared with correlation for CO_2 at airfoil channel. Results from CFD analysis and comparison with correlations are on Table I. Although prediction of the Fanning friction factor is not enough to obtain precise value, correlations for CO_2 at airfoil channel is also acceptable to N_2 at airfoil channel.

Table I: CFD results and error of correlations

Name	Value
Mass flow rate (g/s)	1.80
Heat transfer rate (W)	2.110
Pressure drop – cold (Pa)	2297
Pressure drop – hot (Pa)	4331
Error of the Nu (cooling) (%)	0.8
Error of the Nu (Heating) (%)	0.8
Error of the Fannig friction factor (%)	15.9

3. PCHE design condition

Temperature, pressure, effectiveness and mass flow rate are required to design PCHE. The recuperator condition of N_2-PCS design for ASTRID, French SFR is used with small estimations. PCS of ASTRID is composed of 2 units and each of them has 750MW thermal power. Detailed information of recuperator at PCS of ASTRID is on Table II and Fig.3. Exact value of hot side pressure and effectiveness of recuperator for N_2-PCS of ASTRID is unknown. Consequently, estimated pressure and effectiveness include small estimations.

Table II: Design condition of the N_2-PCS recuperator for ASTRID

	Hot	Cold
Inlet temperature [C]	381	74
Pressure [MPa]	8.5	18.0
Mass flow rate [kg/s]	4246	
Effectiveness	0.95	
Heat transfer [MW]	1333	

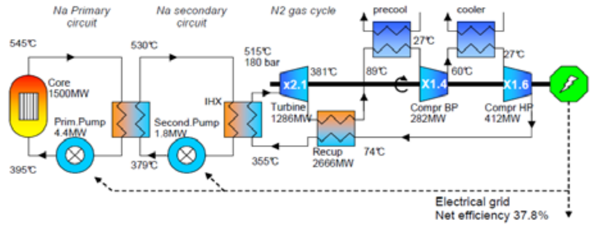

Fig. 3. N_2-PCS design of ASTRID [2].

From the given design condition for the recuperator, recuperator design can be obtained by the 1-D PCHE design code. NACA0020 is selected airfoil shape, and its chord length is 6.0mm. Depth of airfoil channel is 0.8mm, and thickness of PCHE plate is 1.5mm. Various airfoil configurations and mass fluxes are selected factor for this research. 3 Horizontal number (ζ_h=2.0, 2.75, 3.5) and 3 vertical number (ζ_v =2.0, 2.75, 3.5), total 9 cases are analyzed with 200 kg/m^{2}s to 700 kg/m^{2}s mass flux range. Range of the Reynolds number is 10,000 to 30,000, which satisfies modified Dittus-Boelter and Blasius correlation for airfoil channel. Horizontal number and vertical number are distance of airfoil row and column which are normalized by chord length and width. Fig. 4 and eqs. 9-10 show the definition of horizontal and vertical number.

$$\zeta_h = L_h / L_c \quad (9)$$

$$\zeta_v = L_v / L_t \quad (10)$$

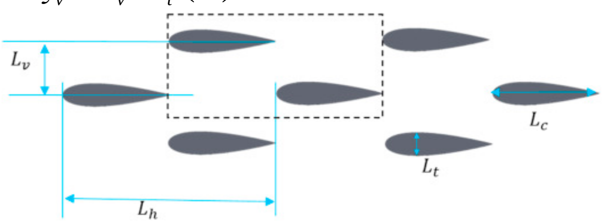

Fig.4. Definition of horizontal and vertical number [4].

4. Results

4.1 Effect of mass flux

Fig. 5 shows the volume of designed PCHEs for various mass fluxes. Volume of PCHE decrease as a function of mass flux, because inlet area of PCHE and mass flux are inverse proportion, but length of PCHE slowly increases as a function of mass flux. Consequently, volume of PCHE is small at high mass flux condition, and large at small mass flux condition.

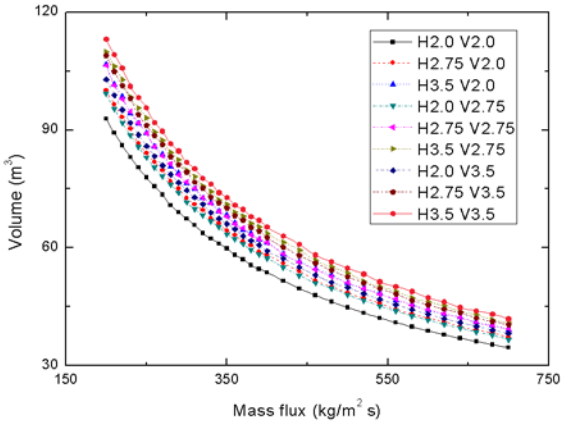

Fig. 5. Volume of designed PCHEs following mass flux.

Figs. 6, 7 show the pressure drop of designed PCHEs. Pressure drop of PCHE means energy loss of working fluid at same mass flow rate. Velocity of working fluid is proportional to mass flux and pressure drop is proportional to square of velocity. However, decrease of the Fanning friction factor is smaller than square of velocity. As a result, pressure drop is high at high mass flux.

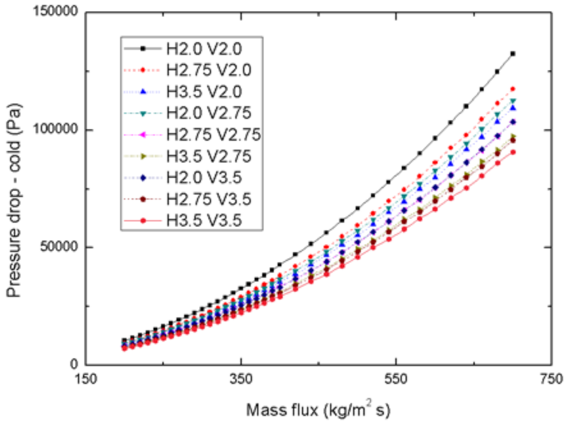

Fig.6. Cold channel pressure drop of designed PCHEs.

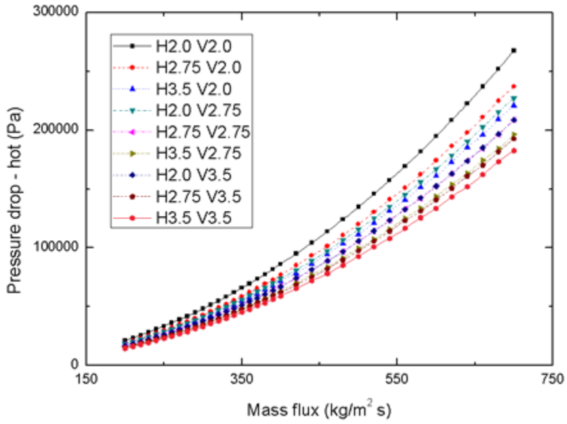

Fig. 7. Hot channel pressure drop of designed PCHEs.

4.2 Effect of horizontal/vertical number

Fig. 8 shows the volume of designed PCHEs for various horizontal and vertical number. Volume of PCHE increases following increase of vertical number and horizontal number at same mass flux. Small horizontal and vertical number mean that airfoils are more concentrated to same volume. Consequently, small horizontal and vertical number case have high compactness, and volume of PCHE which satisfies effectiveness of the recuperator is small.

Figs. 9, 10 show the effect of horizontal and vertical number to pressure drop. Pressure drop decreases as a function of vertical number and horizontal number at same mass flux. Similarly to volume of PCHE, meaning of small horizontal and vertical number is dense arrangement of airfoil. As a result, high horizontal and vertical number cases have small flow resistance, and low pressure drop shows the result of small flow resistance. Density of hot channel is smaller than cold channel due to pressure difference (8.5 MPa, 18 MPa). Consequently, velocity of hot channel is faster than cold channel. Pressure drop of hot channel is higher than cold channel.

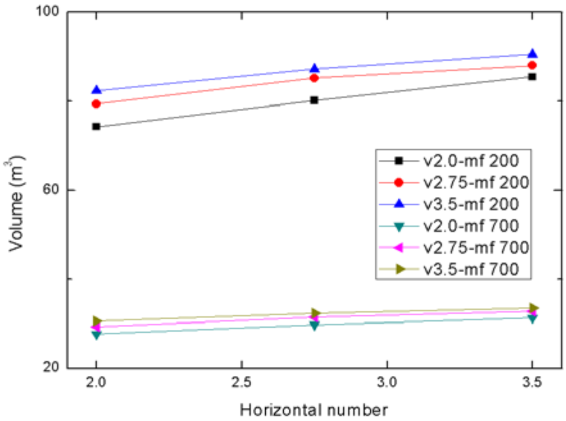

Fig. 8. Volume of designed PCHE following horizontal and vertical number.

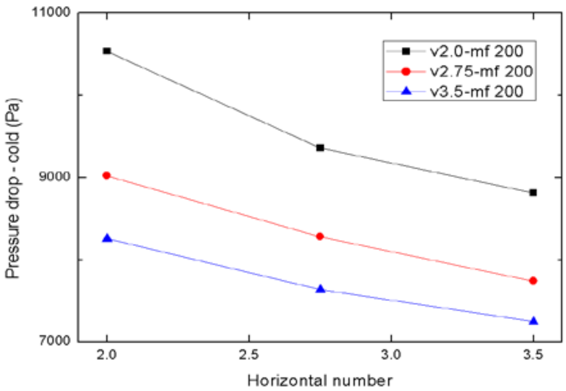

Fig. 9. Cold channel pressure drop of designed PCHE.

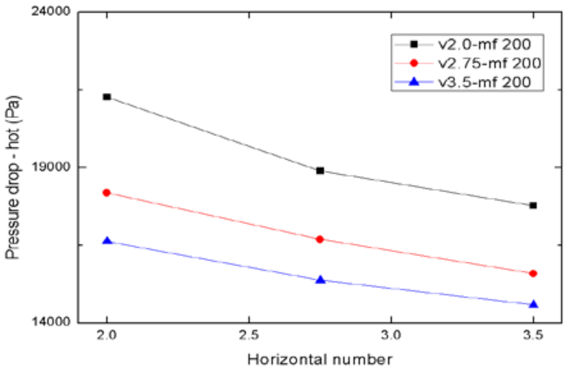

Fig. 10. Hot channel pressure drop of designed PCHE.

4.3 Comparison with the ASTRID recuperator

There is no information about type of PCHE which is used for design of the recuperator of ASTRID. Although, comparison between preliminary design of airfoil PCHE which is restricted by the recuperator design condition of ASTRID and preliminary design which is suggested by Alpy for the recuperator of ASTRID can evaluate airfoil channel PCHE. Table III shows the detailed description of preliminary design of ASTRID recuperator suggested by Alpy and this research [2].

Table III: Preliminary design of ASTRID recuperator by Alpy and this research

	ASTRID	Min vol.	Min ΔP
Volume(m^3)	158.4	62.2	113.1
Compactness (MW/m^3)	8.4	21.4	11.8
ΔP_cold(bar)	0.3	0.29	0.07
ΔP_hot(bar)	0.6	0.59	0.15

Airfoil configurations and mass fluxes which satisfy pressure drop condition, 0.6 bar for hot side and 0.3 bar for cold side are selected for comparison. Minimum volume case shows 0.29 bar and 0.59 bar for cold side and hot side pressure drop. Volume is 62.7 m^3. Mass flux of minimum volume case is 360 kg/m^2s with 2.0 of horizontal number and 2.75 of vertical number. Volume of minimum volume case is 2.46 times smaller than the preliminary design of ASTRID recuperator. Pressure drop of minimum pressure drop case is one-fourth of restriction, and volume of PCHE is still smaller than the preliminary design of ASTRID recuperator. Mass flux of minimum pressure drop case is 200 kg/m^2s with 3.5 of horizontal number and 3.5 of vertical number. As a result, airfoil PCHE shows the outstanding performance of pressure drop and high compactness.

5. Conclusion

To remove SWR, N_2-PCS was suggested for PCS of SFR. PCHE is the best option for heat exchanger of Brayton cycle, due to high compactness and wide operation range. In this research, preliminary design of airfoil PCHE for N_2-PCS recuperator is performed. Design condition is obtained from N_2-PCS design for French SFR, ASTRID. From CFD analysis, the Nusselt number and the Fanning friction factor correlation for SCO_2 Brayton cycle recuperator condition is also acceptable N_2-PCS recuperator condition. Compactness and pressure drop performance of airfoil PCHE are superior to preliminary design of ASTRID recuperator.

However, optimization of airfoil PCHE is still required. Previous optimization methods with cost-based weight of performance factor did not considered construction cost of containment due to volume of heat exchanger. Power generation cost analysis for SFR will be considered for cost-based optimization methods [4]. Consequently, more research of design and optimization methods of airfoil PCHE are required for SFR with N_2-PCS.

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