Proceedings of the 10th International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'23)
Ottawa, Canada – June 07-09, 2023
Paper No. 182
DOI: 10.11159/ffhtm23.182

1D Modelling of Printed Circuit Heat Exchanger for Demo Fusion Power Plant

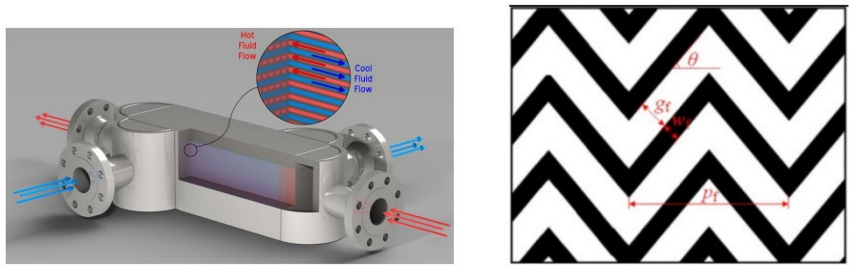
Matyáš Junek[1,2], Jan Štěpánek[1], Guk Chol Jun[1], Pavel Zácha[1], Slavomír Entler[1,2]
[1]Department of Energy Engineering, Faculty of Mechanical Engineering,
CTU in Prague, Czech Republic
matyas.junek@fs.cvut.cz; j.stepanek@fs.cvut.cz
[2]Institute of Plasma Physics of the Czech Academy of Sciences,
Prague, Czech Republic
kukchol.jun@fs.cvut.cz

Abstract **-** The power conversion system will be an important part of the DEMO fusion power plants. One possible way to convert heat from a helium-cooled fusion reactor to electricity is by the Brayton cycle with supercritical carbon dioxide (sCO2) as a working fluid. This approach offers a smaller footprint and smaller initial cost of the system than the Rankine cycle does, mainly due to the small size of the turbomachinery and simplicity of the Brayton cycle. Heat exchangers (heaters, coolers, and recuperators) play a major role in the overall size and cost of the system. One of the most promising heat exchanger types for heaters and recuperators is printed circuit heat exchangers (PCHE). In this work, the size of PCHE between primary circuit and secondary circuit with sCO2 of the helium-cooled DEMO power plant is computed using Python script. Presented results show that overall volume of heaters for the DEMO strongly depends on channel geometry.

Keywords**:** supercritical carbon dioxide, DEMO power plant, printed circuit heat exchanger, nuclear fusion, Brayton cycle, parametric model

1. Introduction

The reactor blanket of the DEMO fusion power plant will be cooled with helium or water [1]. Usage of helium leads to higher outlet temperature at which the indirect Brayton secondary cycle with sCO2 (sCO2 Brayton cycle) reaches relevant efficiency, and thus can be considered as an alternative to the well-known Rankine cycle [2]. Although the Rankine cycle in DEMO would provide higher efficiency than the sCO2 Brayton cycle [3], Brayton offers several advantages; such are a lower number of main components, less complexity, smaller size of turbomachinery, and thus lower initial cost [4][5][6]. The largest components of sCO2 Brayton circuits are heat exchangers (HE); either heaters, recuperators, or coolers. That is why compact (high ratio of heat transfer area and volume of HE) HEs are required for such an application. One of the most promising types of compact heat exchangers is Printed circuit heat exchangers (PCHE) (Figure 1a). PCHE consists of thick plates with chemically etched microchannels in which fluid flows. Plates for hot and cold fluid are stacked to each other and then diffusion bonded, which results in joints with excellent mechanical properties. Number of materials can be diffusion bonded including some special alloys (alloy 617) that are ideal for high pressure, high temperature and corrosive environments. The geometry of microchannels varies based on a specific application. Channels can be straight or "zig zag". The performance of PCHE with zig zag (Figure 1b) [7] channels depends on geometric parameters with wave angle θ being the most significant parameter. In some applications, it is beneficial to enhance heat transfer area or free flow area in one side (for example hot) by using two hot plates for one cold plate (double plate). The goal of this study is to determine approximate size of PCHE in the DEMO power plant between helium cooled primary circuit and secondary circuit with sCO2 as a working fluid considering different possible channel geometries and PCHE arrangements.



(a) Printed circuit heat exchanger

(b) zigzag microchannels geometry [8]

Figure 1 Printed circuit heat exchanger

2. Method

Size of heaters for DEMO are determined due to in-house python code. Three geometries of micro-channels were considered: straight channels, zigzag with wave angle $\theta = 32.5°$ and zigzag with $\theta = 40°$. Single plate and double plate for the hot side are taking into account for each channel geometry. The python code is based on 1D computational model. Fluid properties are obtained from CoolProp library [9].

2.1 Computational code

After data input, program starts by optional mechanical design computing. Plate thickness, wall thickness, and side margins can be determined due to ASME code [10]. The computation of basic heat balance follows. In the next step, the size of the PCHE is estimated for the reduction of computational time. In main computing part, overall cold side enthalpy difference is divided into n nodes (Figure. 2). In each node, thermohydraulic characteristics and the length of the element are determined. When the whole enthalpy difference is computed, the computed pressure drop and required pressure drop are compared. If the difference is acceptable, output data are written into a file, and the program ends. Otherwise, the free flow area is changed, and a new iteration starts. The log mean temperature difference method is employed to determine the cold side heat transfer area. The overall heat transfer coefficient U is given by following equation:

$$U = \frac{1}{\frac{1}{\alpha_c} + \frac{t_{kd}}{\lambda} + \frac{A_c}{A_h \alpha_h}} \tag{1}$$

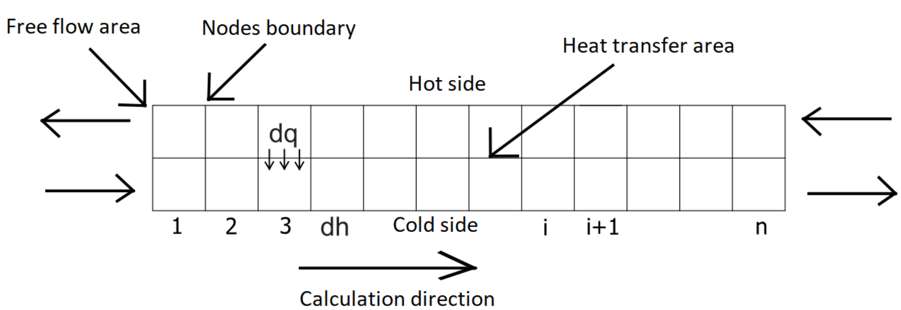


Figure 2 Computational schema

where α_c and α_h is convection heat transfer coefficient for cold side and hot side respectively, λ is thermal conductivity of material and A_c / A_h is ratio of cold side and hot side heat transfer area. The ratio depends on double plate usage and on the difference between hot side and cold side channel geometry.

Figure 3 AHELLO helium loop

2.2 Corelations

The program can compute PCHE with strait channels and with "zig zag" channels for wave angle 32.5° and 40°. Lack of available correlations, especially for higher Reynolds numbers does not allow to implement more geometries into the program and enhance optimalization. For straight channels proven Gnielinski correlation [8] is used. Gniellinski correlation is valid for supercrtical conditions [11]. This correlation is suggested by Mylavarapu et al. [12][13][14] for gasses in PCHEs within turbulent regime. Gnielinski correlation:

$$U = \frac{2f(Re - 1000)Pr}{1 + 12.7(Pr^{\frac{2}{3}} - 1)\sqrt{2f}}, \tag{2}$$

$$f = \left(\frac{1}{1.82\log(Re) - 1.64}\right)^2. \tag{3}$$

Where Nu is Nusselt number, Re Reynolds number, Pr Prandtl number and f Darcy friction factor. For "zig zag" channels Kim's correlations [15] were applied. For wave angle θ = 32, 5 ◦ and Re ∈ (2000; 55000):

$$Nu = 0.0292Re^{0.8138}, \tag{4}$$

$$f_f = 0.2515Re^{-0.2031}. \tag{5}$$

For θ = 40◦ and Re ∈ (2000; 55000):

$$Nu = 0.0188Re^{0.8742}, \tag{6}$$

$$f_f = 0.2881Re^{-0.1322}. \tag{7}$$

Where f_f is Fanning friction factor.

2.3 Validation

The program was validated due to experiments with PCHE in He/He loop AHELLO [16] (Figure 3). Loop was assembled in ATEKO a.s to verify the parameters of high-temperature HEs. Measured experimental data such as inlet and outlet temperatures, pressure drop, or thermal power were used as inputs for the program. The computed size of PCHE was compared with the size of the actual experimental PCHE. Comparison of 1D model and experiments are in Table 1. Comparison shows good agreement with experimental and computed values. Thus the program can be considered valid.

Table 1 Validation of 1D model

Experiment	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Thermal power (experiment) [MW]	182.8	252.8	310	365.6	596.6	725.7	888
Thermal power (model) [MW]	187.1	242.9	273.5	292.6	582.3	722.7	877.4
Deviation of thermal power [%]	2.3	4.1	13.3	24.9	2.5	0.4	1.2
Pressure drop (hot-experiment) [Pa]	2842	4480	6142	-	4611	4631	4663
Pressure drop (ho-model) [Pa]	2764	4052	5187	6611	5110	5164	5694
Deviation of pressure drop (hot) [%]	2.8	10.6	18.4	-	9.8	10.3	18.1
Pressure drop (cold-experiment) [Pa]	2613	4063	5932	-	4329	4391	4440
Pressure drop (cold-model) [Pa]	2583	3710	4705	5976	4301	4266	4601
Deviation of pressure drop (cold) [%]	1.2	9.5	26.1	-	0.7	2.9	3.5

2.1 Inputs parameters

Input parameters for helium-cooled DEMO with sCO2 secondary circuit were provided by Štěpánek [3] and can be found in Table 2.

Table 2 Input parameters

Parameter	**Value**
Thermal power [MW]	2197.8
Hot side inlet temperature [°C]	520
Cold side inlet temperature [◦C]	510
Hot side mass flow rate [kg/s]	1842
Cold side mass flow rate [kg/s]	7354
Hot side inlet pressure [MPa]	8.16
Cold side inlet pressure [MPa]	34.07
Hot side maximum allowable pressure drop [MPa]	0.3
Cold side maximum allowable pressure drop [MPa]	0.681
Effectiveness [%]	96

3. Results

Overall 3 types of PCHE with different channel geometry were computed:

- straight channels,
- zig zag with $\theta = 32.5^\circ$,
- zig zag with $\theta = 40^\circ$.

PCHE with a single plate and a double plate for the hot side was computed for each channel geometry. Comparison of PCHE's core volumes is in Figure. 4 (DP = double plate for hot side). PCHE with the lowest core volume is the one with wave angle $\theta = 32.5^\circ$ and with a double plate for the hot side. For each channel geometry, the double plate configuration exceeds the single plate configuration.

Table 3 Computational results

Parameter	***θ* = 0**	***θ* = 32.5°**	***θ* = 40°**
Height power of single unit [m]	7.2	6.14	6.61
Width power of single unit [m]	0.6	0.6	0.6
Length power of single unit [m]	1.24	0.925	1.32
Volume power of single unit [m^3]	5.35	3.41	5.24
Thermal power of single unit [MW]	45.8	34.3	54.9
Num. of parallel HEs [3]	16	32	40
Num. of serial HEs for each parallel [3]	3	2	1
Volume of all HEs [m^3]	257.1	218.1	209.6

As per Heatric [7] (PCHE manufacturer), the maximum plate size is 0.6 x 1.5 m. The plates can be stacked to each other and diffusion bonded to a maximum height of 1 m, but those blocks can be bonded together to a maximum height of 8 m. These units can then be joined into parallel or series. However, the side margins, end margins, and headers must be considered in each block. If doing so, the overall volume of PCHE increases. The dimensions and overall volumes for each channel geometry can be seen in Table 3. The PCHE with the smallest overall volume would be configuration with ”zig zag” channels (θ = 40°) and with double plate for the hot side. In the helium-cooled DEMO power plant with sCO2 Brayton secondary circuit would be needed 40 PCHEs with dimensions 6.61 x 0.6 x 1.32 m to transfer heat between primary and secondary circuits. In this case, the variant with wave angle θ = 40° and with a double plate for the cold side would be the most beneficial with the overall volume of HEs 209.6 m^3.

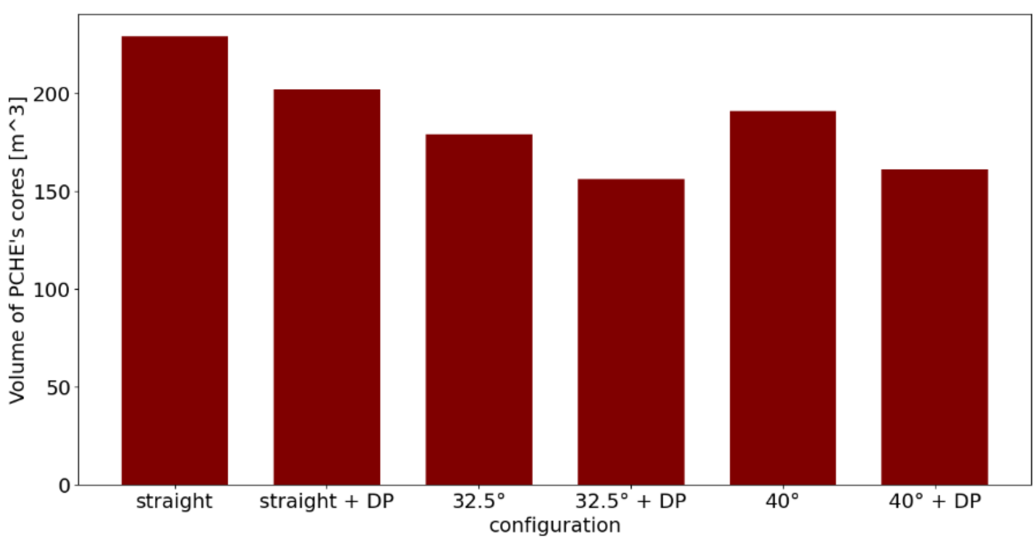


Figure 4 Volume of PCHE’s cores (DP = double plate for hot side)

4. Discussion

The results presented in this paper are valid for the given parameters. The size of actual heaters in DEMO varies with different input parameters. For example, PCHE's volume depends on required efficiency. Size of PCHE can be probably lowered by optimization of channel geometry, but correlations for more geometries, especially for higher Re, are not publicly available.

5. Conclusion

The size of PCHEs in the DEMO power plant between primary and secondary circuits for given input parameters was successfully determined by 1D computational model. Three channel geometries were considered. Total volume of PCHEs with straight channels, zigzag with $\theta = 32.5°$ and zigzag with $\theta = 40°$ is 257 m3, 218.1 m3 and 209.6 m3 retrospectively. The size could be further reduce by considering more channel geometries.

Acknowledgements

The work was supported by European Regional Development Fund - Project "Center for Advanced Applied Science" (No.CZ 02.1.01/0.0/0.0/16e019/0000778), TACR project TK03030087, and by the Strategy AV21 of the Czech Academy of Sciences within the research program "Sustainable Energy".

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