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CFD ANALYSIS OF A PRINTED CIRCUIT HEAT EXCHANGER (PCHE) APPLIED TO A NUCLEAR FUSION REACTOR

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Abstract. Nuclear fusion research has been growing over the past few decades since fusion is viewed as an alternative source of sustainable energy. The cooling system of a fusion reactor is complex and requires modern technologies to suit the operation. In this context, the printed circuit heat exchangers (PCHEs) are promising due to their compactness, high temperature resistance and high effectiveness. There are no studies in the literature considering high Reynolds number helium flows in PCHE zigzag channels, which makes it important to develop numerical correlations for the heat transfer and the pressure drop under these conditions. The objective of this study is the analysis of heat transfer and pressure drop in a PCHE with hot and cold layers of zigzag channels alternated vertically, with semicircular cross sections, under the conditions of the ITER fusion reactor. In both the hot and the cold streams, the considered working fluid was helium at the pressure of 8.0 MPa and at a high Reynolds number (Re) range (from 5,000 to 40,000 for the hot fluid and from 20,000 to 55,000 for the cold fluid). The values of zigzag angle α considered were 15° , 30° and 45° . The problem was solved by the finite elements method, using the commercial software ANSYS Fluent v.18.2. A three dimensional, steady-state model was implemented, using the $k-\omega$ SST turbulence model. The average Nusselt number and the average friction factor were calculated considering the range of parameters employed. The Nusselt number was found to increase with Re and α , while the friction factor increased with α and decreased with Re . New correlations have been proposed for the Nusselt number and the friction factor over the wide range of turbulent Reynolds numbers studied.

Keywords: CFD, PCHE, nuclear fusion, heat transfer, pressure drop, helium

1. INTRODUCTION

Nuclear energy plays an important role in the search for clean energy sources. All existing commercial reactors are based on nuclear fission technology, which produces waste and is not renewable, although clean. On the other hand, nuclear fusion stands as one of the world's biggest engineering challenges. Despite the potential to fulfil the world's increasing demand for clean, renewable and safe energy, up to the moment, only a few research reactors are in operation and the technology still has a long journey ahead before it proves to be economically favorable.

Among the most promising research projects, the *International Thermonuclear Experimental Reactor* (ITER) is a collaborative enterprise between 35 countries with the aim of building the world's largest fusion reactor and advancing the research in nuclear fusion. The cooling system of the ITER consists of a blanket module and an auxiliary system. The blanket module is a structure, built on the outer walls of the reactor, through which a coolant flows and absorbs energy coming from the plasma — where the fusion reaction takes place. The auxiliary system is the secondary structure through which the heated coolant flows, gets cooled by water and is then sent to the steam generator.

Ricapito *et al.* (2016) presented the auxiliary system of the ITER reactor where the coolant is high pressure helium gas. In this system, the helium stream entering the blanket is heated by an electric heater and by the hot helium stream that

comes out of the blanket itself. The heat exchanger used to heat the helium is intended to decrease the charge demanded by the electric heater. One of the types of exchangers considered for this function is the Printed Circuit Heat Exchanger (PCHE).

Printed Circuit Heat Exchangers (PCHE) are a type of compact exchanger formed by flat metal plates with chemically etched channels. Their advantages, when compared to traditional shell and tube heat exchangers, include high performance, compactness, high temperature and pressure resistance, while the main disadvantage is the high pressure drop (Pierres *et al.*, 2011).

Ma *et al.* (2015) conducted a study of a PCHE with alternating layers of hot and cold zigzag channels utilizing helium as both the hot and the cold fluid, under the conditions of a Very-High-Temperature Reactor (VHTR). The geometry used served as the basis for the present work since its configuration and dimensions represent the most typical PCHEs found in literature.

Many researchers have studied the thermal-hydraulics of PCHE with zigzag channels, both experimentally (Berbish *et al.*, 2011; Chen *et al.*, 2016; Nikitin *et al.*, 2006; Chu *et al.*, 2020; Cheng *et al.*, 2020; Chen *et al.*, 2019; Kim *et al.*, 2009; Kim and No, 2011, 2013; Chen *et al.*, 2018; Baik *et al.*, 2017) and numerically (Chen *et al.*, 2019; Kim *et al.*, 2009; Kim and No, 2011, 2013; Chen *et al.*, 2018; Baik *et al.*, 2017; Kim and Sun, 2014; Kim *et al.*, 2016; Lee and Kim, 2013; Ma *et al.*, 2015, 2019; Meshram *et al.*, 2016; Pan *et al.*, 2020; Yoon *et al.*, 2014, 2017; Kim *et al.*, 2010; Bennett and tung Chen, 2019; Kim *et al.*, 2008; Ma *et al.*, 2017). However, most correlations developed for estimation of the heat transfer and the pressure drop cover a range of Reynolds numbers up to 3,558, for helium (Chen *et al.*, 2016). For high Reynolds numbers, there are only few correlations (Berbish *et al.*, 2011; Kim *et al.*, 2016), valid for a limited number of zigzag angles and specific fluids — the most common fluid is the supercritical CO₂, which typically presents different properties as, in most cases, it experiences a wide variation of properties due to the pseudocritical transition taking place within the heat exchanger.

Kim *et al.* (2016) is the only work, up to the moment, to have proposed correlations for a PCHE with zigzag channels under high Reynolds numbers ($2,000 \leq Re \leq 58,000$ for the cold fluid and $2,000 \leq Re \leq 55,000$ for the hot fluid). The authors considered the supercritical CO₂ as both the hot and the cold fluid. Berbish *et al.* (2011) performed the experimental study of a PCHE straight channel and semicircular cross section, with air being heated by a uniform wall heat flux, in the turbulent regime ($8,242 \leq Re \leq 57,794$), and developed new correlations for the Nusselt number and the friction factor.

The objective of this work is the analysis of the heat transfer and pressure drop in a PCHE used in the auxiliary system of the ITER reactor, with semicircular cross section and zigzag channels with different bending angles (15° , 30° and 45°) for turbulent helium ($5,000 \leq Re \leq 40,000$ for the hot fluid and $20,000 \leq Re \leq 55,000$ for the cold fluid). This analysis shall be carried out by CFD simulations, the obtained results shall be compared to the existing correlations in the literature and, lastly, correlations shall be proposed for the Nusselt number and the friction factor of both the hot and the cold streams.

2. METHODOLOGY

The CFD simulations were performed with ANSYS Fluent v. 18.2, where the transport equations are solved by the finite volumes method. The geometry and mesh were built in ANSYS Design Modeler and ANSYS Meshing, respectively.

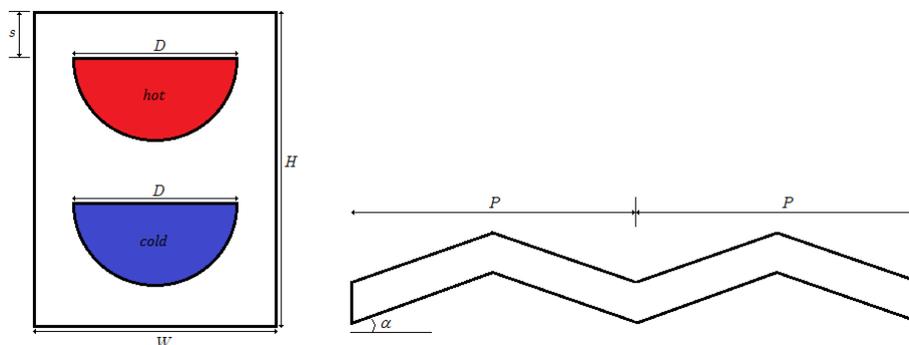


Figure 1: Cross section and longitudinal section of the physical model of a PCHE.

Figure 1 shows the geometry of the physical problem, based on the geometry used by Ma *et al.* (2015). It consists of a PCHE with alternating layers of hot and cold channels flowing in countercurrent. Helium gas was utilized as the cold and the hot fluid. By considering the channels parallel to each other within the entire heat exchanger, the physical model can be represented by a single repeating unit, consisting of a hot and a cold channel inside a block of steel with periodic

boundary conditions applied at the sides, as shown in Fig. 1. The geometry of both channels is identical. D is the channel diameter, H , the height, W , the width, s , the space between the channel and the wall. P is the pitch of the channel (the length of a single zigzag), and α is the zigzag angle.

For the CFD simulations, the hypotheses and boundary conditions used were: steady state, incompressible ideal gas, constant properties for the the solid, turbulent flow with $k - \omega$ SST model, periodic boundary conditions at the top, the bottom and the side walls, gauge pressure equal to zero at the outlets, uniform velocity at the inlets.

The helium properties, except for the density, were implemented as functions of the temperature and were obtained from the NIST REFPROP v. 9.1 database(Lemmon *et al.*, 2018). The density of helium was obtained from the incompressible ideal gas law. The solid block is made of Alloy 617.

The governing Navier-Stokes equations and energy equation are written as follows:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\rho_f (\nabla \cdot \mathbf{u}) = \nabla \cdot [-p \mathbf{I} + \mu_f (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] \quad (2)$$

$$\rho_f C_{p_f} (\mathbf{u} \cdot \nabla T_f) = \nabla \cdot (k_f \nabla T_f) \quad (3)$$

where \mathbf{u} is the velocity, ρ_f , C_{p_f} , k_f are, respectively, the density, specific heat and thermal conductivity of the fluid. p stands for the pressure and T_f is the temperature of the fluid.

The energy equation for the solid is:

$$\nabla \cdot (k_s \nabla T_s) = 0 \quad (4)$$

where k_s is the thermal conductivity and T_s is the temperature of the solid.

3. RESULTS AND DISCUSSION

The simulations were performed considering the same geometric parameters used by Ma *et al.* (2015): $D = 1.51mm$, $H = 2.92mm$, $W = 2.62mm$, $s = 0.35mm$, $P = 24.6mm$. Three different zigzag angles were considered (15° , 30° and 45°).

The simulation parameters for the helium channels were considered according to Ricipito *et al.* (2016). The inlet temperature of the hot channel was $683.15K$ and the inlet temperature of the cold channel was $323.15K$. The outlet gauge pressure was zero for both channels and the operation pressure was $8.0MPa$.

A wide range of Reynolds numbers in the turbulent regime was considered for each channel. Eight simulations were performed for each angle — totaling a set of 24 simulations, increasing the Reynolds number by 5,000 from one case to the other. The Reynolds number ranged from 5,000 to 40,000 at the hot channel and from 20,000 to 55,000 at the cold channel. The Prandtl number for helium ranged from 0.76 to 0.78 throughout the simulations set.

A mesh convergence study was carried out in the three different geometries (15° , 30° and 45°) with different zigzag angles. Four increasingly refined unstructured meshes were generated for each geometry and simulations were performed with each one. The global Nusselt number in the hot and cold channels was calculated and found to vary less than 1% from the third to the fourth meshes, for all geometries. Thus, the third meshes were chosen for the further simulations. The chosen meshes for each geometry presented around 5 million elements and a near wall refinement with y^+ around 1.0, which is consistent to the turbulence model used.

For verification purposes, a set of simulations was performed under the same conditions of Ma *et al.* (2015). The differences when compared to the cases described above are that these verification simulations are under the laminar regime, with Reynolds numbers of 400, 800, 1,200, 1,600 and 2,000; the inlet temperature of the hot and the cold channels are $1,173K$ and $813K$, respectively, and the operating pressure is $3.0MPa$. For these simulations, only the geometry with the zigzag angle of 30° was considered.

Figure 2 shows the Nusselt number and the Fanning friction factor, as functions of the Reynolds number. A considerable difference between the results can be explained because the geometry of Ma *et al.* presents straight extensions of the channels in order to reduce the inlet and the outlet effects. These extensions were not considered in this model in order to reduce computational time. As the observed deviation was fairly small (below 10%), the results of the simulations are considered to reasonably agree with the results of Ma *et al.* (2015).

Figures 3 and 4 show the Nusselt number and the Fanning friction factor for the hot and cold channels, respectively, under the conditions of the ITER reactor. The results are compared to the correlations of Berbish *et al.* (2011), for turbulent air in a straight semicircular channel; the correlations of Kim *et al.* (2016), for the supercritical CO_2 in a

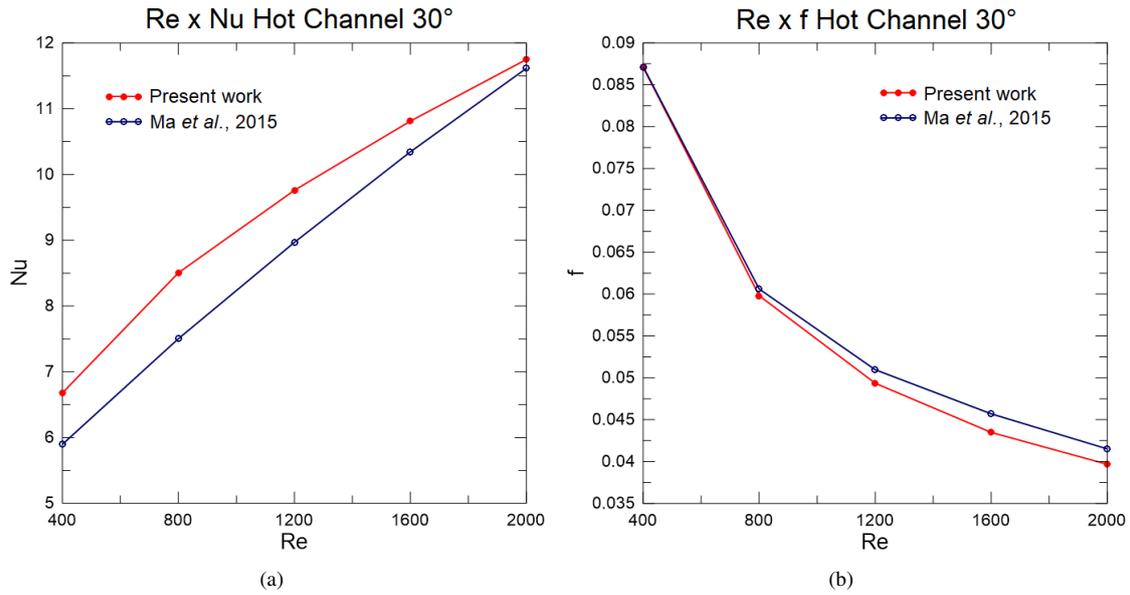


Figure 2: (a) Nusselt number and (b) friction factor as functions of the Reynolds number for the hot channel.

semicircular zigzag channel; and the classic correlations of Gnielinski and McAdams for flows in straight pipes under the turbulent regime. The studied correlations and their applicability ranges are summarized in Table 1.

As expected, the Nusselt number increases with the Reynolds number and the zigzag angle, whereas the friction factor increases greatly with the zigzag angle and decreases with the Reynolds number, presenting a more flattened behavior for higher values of Re . The results are consistent with the studied correlations, taking into account the differences regarding the conditions for which they were developed, such as geometry and type of fluid. The correlations of Berbish *et al.* (2011), Gnielinski and McAdams are for straight channels, therefore their resulting values of Nu and f were below the results presented in this work, as expected. The friction factor and the Nusselt number estimated by the correlations of Kim *et al.* (2016) were above the ones of the present work. These discrepancies indicate that differences between the two fluids may affect the heat transfer and the pressure drop significantly.

Table 1: Studied correlations.

Authors	Correlations	Fluid	Reynolds number	Zigzag angle
Berbish <i>et al.</i> (2011)	$Nu = 0.0228Re^{0.8}$ $f = 0.487Re^{-0.26}$	air	8,242 – 57,794	0°
Kim <i>et al.</i> (2016)	$Nu = 0.0292Re^{0.8138}$ $f = 0.2515Re^{-0.2031}$	CO ₂ (hot fluid) ($0.5 \leq Pr \leq 1.5$)	2,000 – 58,000	32.5°
	$Nu = 0.0188Re^{0.8742}$ $f = 0.2881Re^{-0.1322}$	CO ₂ (cold fluid) ($0.7 \leq Pr \leq 1.0$)	2,000 – 55,000	40°
Gnielinski	$Nu = 0.0214(Re^{0.8} - 100)Pr^{0.4}$	any fluid ($0.5 \leq Pr \leq 1.5$)	2,300 – 5×10^6	0°
McAdams	$f = 0.184Re^{-0.2}$	any fluid	$3 \times 10^4 - 1 \times 10^6$	0°

A nonlinear regression was carried out by Wolfram Mathematica v. 11.3, using the Levenberg-Marquardt method, and disregarding the small Prandtl number variation, the following new correlations have been proposed:

- For the hot channel:

$$Nu = (0.02463 \pm 0.002591)Re^{0.7336 \pm 0.009810} \alpha^{0.2453 \pm 0.009035}$$

$$R^2 = 0.9997,$$

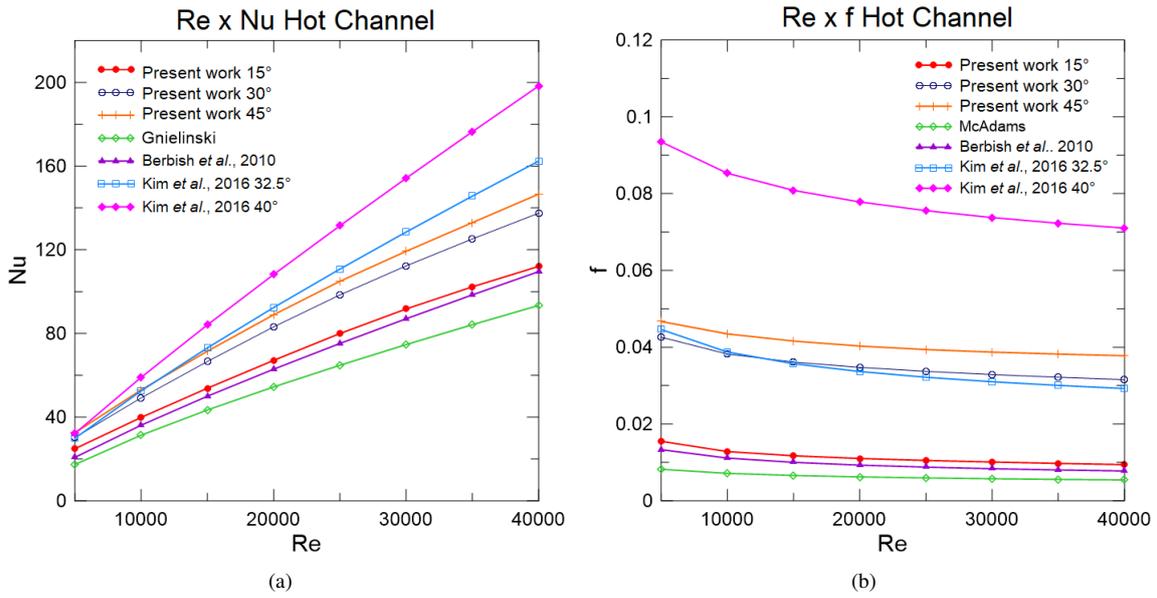


Figure 3: (a) Nusselt number and (b) friction factor as functions of the Reynolds number for the hot channel.

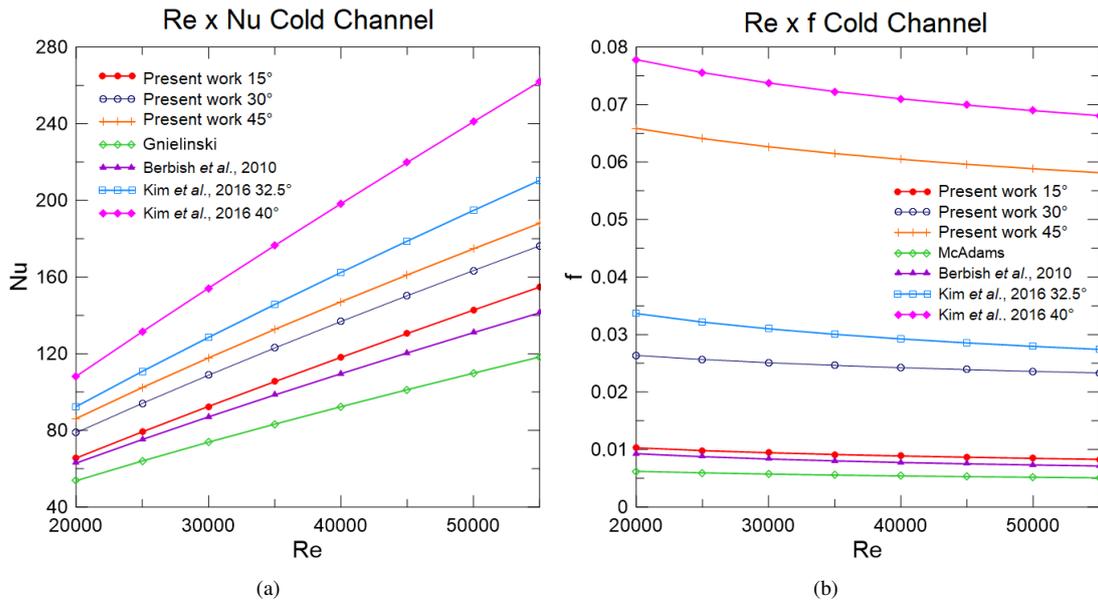


Figure 4: (a) Nusselt number and (b) friction factor as functions of the Reynolds number for the cold channel.

$$f = (0.004210 \pm 0.002278) Re^{-0.1255 \pm 0.04324} \alpha^{0.9351 \pm 0.09422}$$

$$R^2 = 0.981305$$

valid for $5 \times 10^3 \leq Re \leq 4 \times 10^4$ and $0.76 \leq Pr \leq 0.78$.

- For the cold channel:

$$Nu = (0.01444 \pm 0.001159) Re^{0.8001 \pm 0.007399} \alpha^{0.1978 \pm 0.004698}$$

$$R^2 = 0.9999$$

$$f = (0.006319 \pm 0.0001943) + (7.774 \times 10^{-6} \pm 9.731 \times 10^{-7}) Re^{-0.1411 \pm 0.006286} \alpha^{2.717 \pm 0.02880}$$

$$R^2 = 0.9999$$

valid for $2 \times 10^4 \leq Re \leq 5.5 \times 10^4$ and $0.76 \leq Pr \leq 0.77$.

A graphical analysis of the proposed correlations, presented in Fig. 5 and 6, show that, for all cases, the correlations provided estimations within a $\pm 10\%$ deviation range compared to the simulation results, except for the friction factor at the hot channel, which showed a maximum deviation of around 23%.

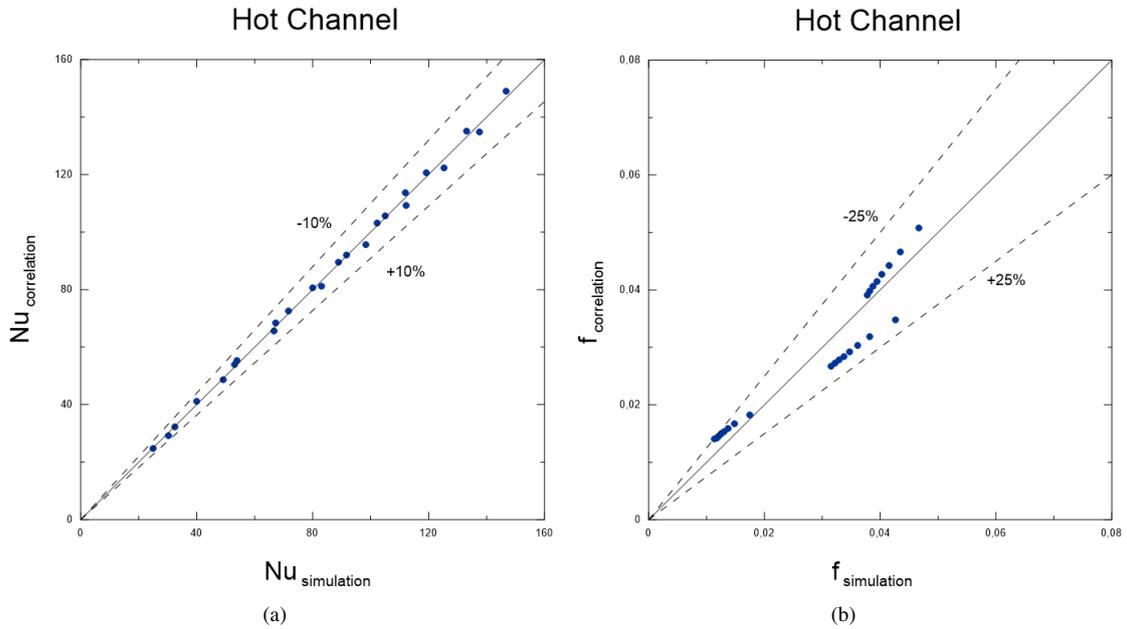


Figure 5: (a) Nusselt number and (b) friction factor provided by the new correlations compared to the simulation results for the hot channel.

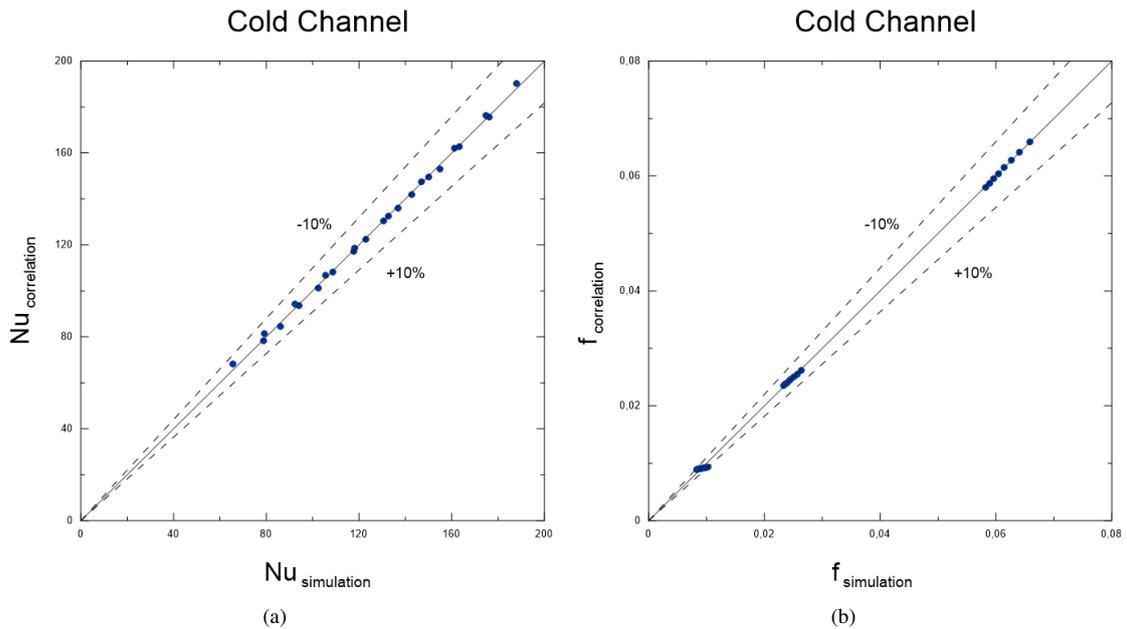


Figure 6: (a) Nusselt number and (b) friction factor provided by the new correlations compared to the simulation results for the cold channel.

4. Conclusion

The thermal-hydraulics of a PCHE with zigzag channels and semicircular cross section, for helium under the conditions of the ITER, was successfully investigated using CFD. A verification was made by comparing the simulation results

to the ones obtained by Ma *et al.* (2015), which showed a good agreement, considering the geometry built by the authors presented channel extensions at inlet and outlet, rather than what was considered in this work.

The Nusselt number increases with the zigzag angle and the Reynolds number. The bigger the angle, the smaller is the Nusselt number enhancement. On the other hand, the friction factor increases greatly with the angle and decreases with the Reynolds number.

The comparison of the results with existing correlations is qualitative, as there are no correlations for the specific set of parameters considered in this work. Nevertheless, the simulation results are in agreement with the existing correlations.

New correlations have been proposed for the Nusselt number and the friction factor, for both the hot and the cold channels. When compared to the simulation results, the correlations provided estimates within the $\pm 10\%$ deviation range, except for the friction factor of the hot fluid, which presented a maximum deviation of 23%.

5. ACKNOWLEDGEMENTS

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