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Towards Optimization of Swirl-Generators for Nuclear Fusion Application

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1. Introduction

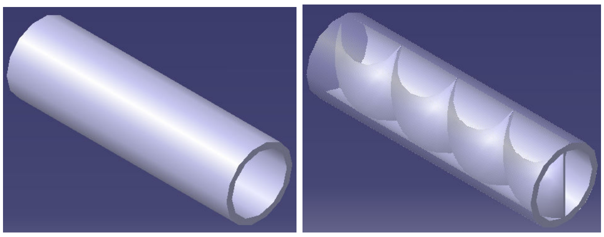
The present trends in development of plasma-facing components (PFCs) fusion power plants are towards higher heat removal capability and lower structural material activation. The critical heat flux is an important criterion in the design of these types of components. Since the burnout condition (i.e., the hot spot expansion) limits the power and operation, the effective management would be advantageous. Several researches have been undertaken in an effort to show that critical heat flux can be increased by enhancement techniques such as hypervaportron, porous coating, screw tubes and swirl tape configuration. Considerations of data base availability for prototypical conditions, lifetime, and compatibility with the preferred monoblock type of option led to the swirl tape being selected as reference configuration for the high heat flux regions of the divertor in ITER [1]. However, recently, the excessive pumping penalty of swirl tape has replaced the configuration to screw tube. Even though the screw tube for initially suggested Cu-alloy as an effective cooling material showed the enough CHF margin, the large amount of neutron load required selection or development of better structural material with much lower thermal conductivity conflicting with higher thermal dissipation of hot spot condition [2]. Even though the lowered CHF margin is not issue of ITER operation, it limits the development of fusion power plants. Therefore, the present work is interested in optimization of the enhancement techniques such as swirl tube with twisted tape and screw tube more effectively and a possibility for compound enhancement concepts of a combination of two or tree existing means or new means. The latter, for example, means the combination of screw tube and swirl tape. The heat transfer enhancement achieved by means of twisted-tape inserts is generally accompanied by an increase in pressure drop. The pressure drop increase causes not only higher pumping power, but it can also alter the heat transfer or CHF values, Thus, in order to optimize the design of a thermal device, both thermal and hydraulic performance must be carefully considered and balanced. This work ultimately aims to optimize the design through comparisons of the overall heat/flow performance (HFP) for heat transfer enhancement means such as swirl tube with twisted tape, screw tube and rifled tube based on CFX simulation work for single phase convection flow. As a preliminary work, this paper shows the results of tubes with twisted-tape inserts.

2. Modeling and Analysis Conditions

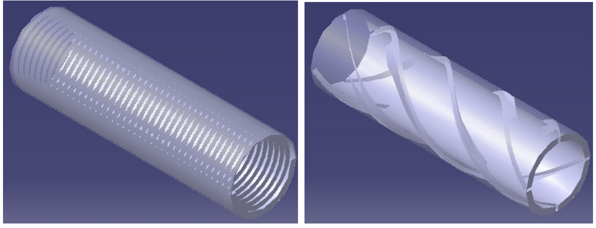
Figure 1 shows a smooth tube and promising swirl-generating tubes to nuclear fusion applications. In order to compare the thermal performance enhancement for each device applicable to the plasma facing components of nuclear fusion power plants, we selected FMS (F82H) as the material of tube. The material has been developed by JAEA for the application in terms of neutron load [2].

For a preliminary work, we selected the swirl tube with twisted tape. The tube geometries are featured with outer diameter of 12 mm, inner diameter of 10 mm and heated length of 400 mm as well as inlet and outlet smooth tube area of 40 mm, respectively. For this tube, the CFX simulation works have been carried out under the following simulation conditions;

- Pressure: 1 MPa (180 ^{o}C T_{sat}),
- Inlet water temperature: 80 ^{o}C (Subcooling 100 ^{o}C)
- Inlet velocity variable: 2, 4, and 6 m/s
- surface heat flux (SHF): 5 MW/m^2 (one-sided heating)



(a) Smooth (b) Swirl Tube



(c) Screw Tube (d) Rifled tube

Figure 1. Promising swirl-generating tubes to nuclear fusion applications

Twisted tape has the geometry of 0.4 mm width and tape ratio of 2 defined by the ratio of the pitch of 180 ^{o} rotation and tube inner diameter.

For simulation domains, solid and fluid meshes were generated separately by using ICEM-CFD.

Table 1. Test Matrix

device	Smooth tube	Twisted tape
Inlet velocity [m/s]	6	2, 4, 6
Inlet water temperature [°C]	80	80
Pressure [bar]	10	10
SHF [MW/m^2]	5.0	5.0

3. Results and Discussion

Figure 2 shows the CFX analysis results such as temperature distribution at heated wall, heat transfer coefficient, and velocity profile at center region. Figure 3 shows the different vector profiles at smooth and swirl tube. The results are summarized in Table 2.

The reference Nusselt number and friction factor are evaluated by Dittus-Boelter equation for turbulent flow and Blasius equation for turbulent flow. The swirl tube reference Nusselt number and friction factor can be evaluated by Gambill et al. [3] as follows;

$$Nu_{Gambill} = \frac{2.18}{y^{0.09}} \cdot Nu_{Dittus\cdot Bolter} \quad (1)$$

$$f_a = \frac{0.00089}{(yD_i^2)^{0.6}} \left(\frac{\mu_i}{\mu_b}\right)^{0.18} \quad (2)$$

Figure 4 shows the comparison between correlation and CFX results.

In order to find the optimal swirl-generators and design parameters, the heat and flow performance of the enhancement methods will be quantified by the overall heat/flow performance (HFP). This can be used to quantify pumping penalty of each enhancement techniques.

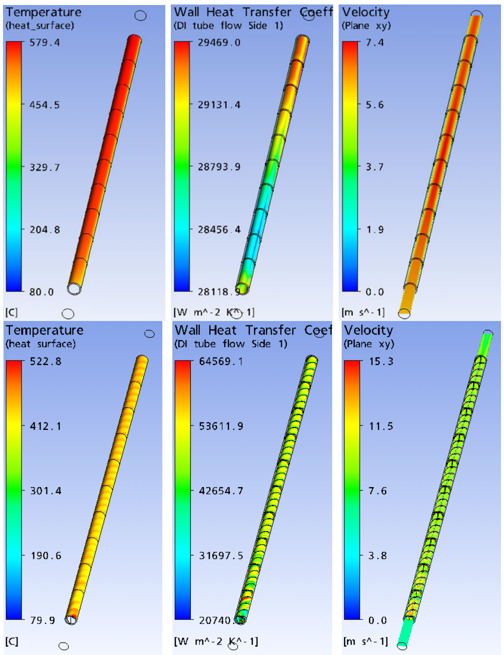


Figure 2. Comparisons between smooth tube and twisted tape (6 m/s)

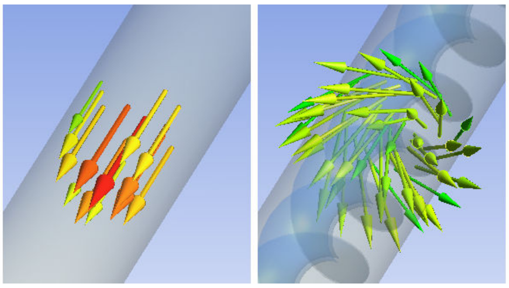
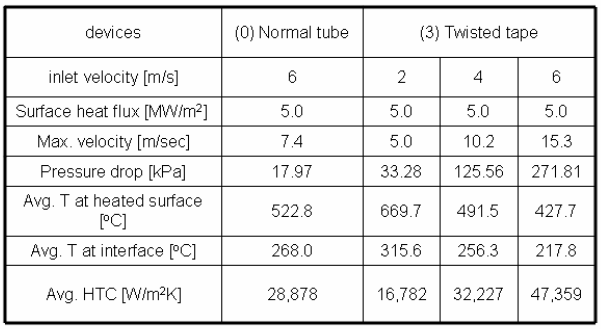


Figure 3. Vector Profile in smooth and swirl tube

Table 3. Heat transfer coefficients and pressure drop



devices	(0) Normal tube	(3) Twisted tape		
inlet velocity [m/s]	6	2	4	6
Surface heat flux [MW/m2]	5.0	5.0	5.0	5.0
Max. velocity [m/sec]	7.4	5.0	10.2	15.3
Pressure drop [kPa]	17.97	33.28	125.56	271.81
Avg. T at heated surface [°C]	522.8	669.7	491.5	427.7
Avg. T at interface [°C]	268.0	315.6	256.3	217.8
Avg. HTC [W/m2K]	28,878	16,782	32,227	47,359

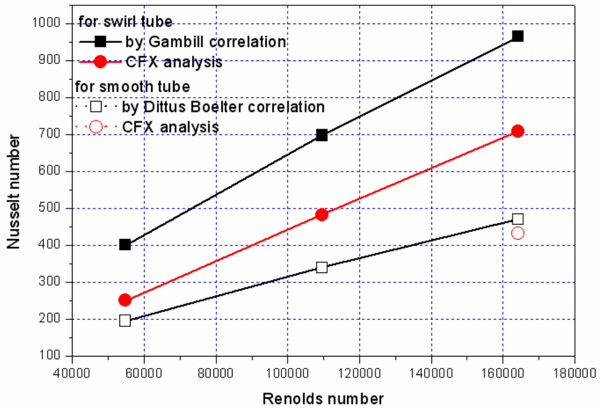


Figure 4. Comparison between the simulation predictions and the available correlations

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