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Thermal Hydraulic Performance Analysis of Smooth and Swirl Tube Type Geometries of Plasma Facing Component Using Entropy Generation Approach

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ABSTRACT

Efficient thermal hydraulic performance is vital in many heat transfer applications such as turbine and condenser of thermal power plants, fuel bundle of nuclear power plants and plasma facing components of ITER or DEMO etc. The heat transfer and pressure drop are two important parameters for designing a thermal system. The performance of such thermal systems can be studied by the entropy generation approach which considers the effect of heat transfer and pressure drop on the performance of any thermal system.

Entropy generation is a measure of the magnitude of the irreversibility present during the process. Irreversibility in the system can be caused by friction, unrestrained expansion of a fluid, heat transfer through a finite temperature difference, and mixing of two different substances. The higher irreversibility in the system corresponds to an increase in entropy generation resulting in a degradation of performance, while a lower irreversibility or entropy generation will result in a better performance. Therefore, entropy generation can be used as a quantitative measure of irreversibility associated with a process.

Plasma facing components in a divertor of ITER or DEMO is subject to very high heat loads coming from plasma. A single-phase flow condition exists in the divertor monoblock during the start-up operation and up to a certain length when it is operating at full power. Thus, the present work aims to evaluate and compare the entropy generation of smooth and swirl tube geometries of ITER like divertor in single-phase flow conditions and also to study the effects of the Reynolds number, Prandtl Number and heated length to hydraulic diameter ratio on entropy generation.

Keywords: *Entropy generation, thermal performance, Swirl tube, ITER Divertor*.

1 INTRODUCTION

Thermal hydraulic performance is very important in many engineering heat transfer applications like heat exchangers, nuclear fuel bundle, and plasma facing component etc. The heat transfer rate in a thermal system can be increased by increasing the flow rate which increases the system pressure drop. The heat transfer rate and pressure drop are two very important parameters in designing any thermal equipment. Irreversibility in a thermal system can be caused by friction, unrestrained expansion of a fluid, heat transfer through a finite temperature difference, and mixing of two different substances [1]. The performance of engineering systems can be determined by the irreversibility present in the system. The entropy generation is a measure of the magnitudes of the irreversibility. Thus, the performance of a thermal system can be improved by minimizing the total entropy generation in the system [2]. A study of the overall entropy generation in the system can help designers understand which parameter influences entropy generation. The designer can then make a final decision to determine the most appropriate design parameters based on these projections.

The objective of the work presented here is to evaluate and compare the total entropy generation of smooth and swirl tube geometries of International Thermonuclear Experimental Reactor (ITER) like divertor test mock-up. A typical smooth and swirl tube configuration are shown in Figure 1. In addition to it, the effects of Reynolds number, Prandtl number and heated length to hydraulic diameter ratio on entropy generation is also investigated.

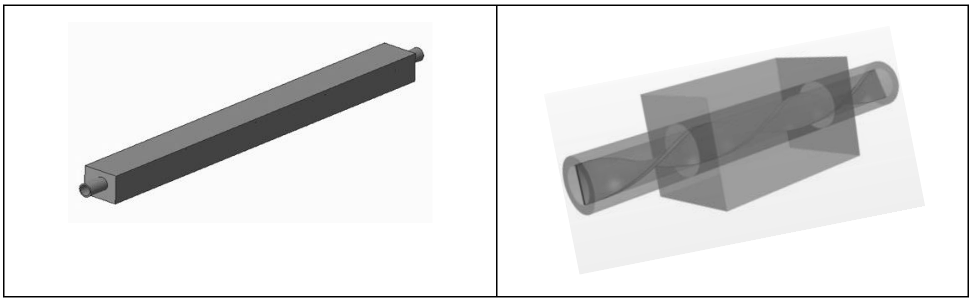


Figure 1: (a) Smooth tube monoblock (b) Swirl tube monoblock

2 DERIVATION OF ENTROPY GENERATION FOR PFC'S MONOBLOCK

The entropy generation for internal fluid flow [3,4] is used for deriving entropy generation for Plasma Facing Component (PFC's) monoblock. The entropy generation for a control volume is shown in Figure 2.

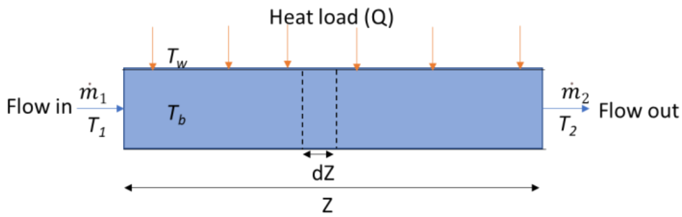


Figure 2: Schematic of single-phase water flow in test mockup

According to second law of thermodynamics, Entropy generation is derived for a control volume can be expressed as follows

$$dS_{gen} = \dot{m}dS - \frac{dQ}{T_w} \tag{1}$$

where dS_{gen} is rate of entropy generation (W/^{0}C)
dZ is incremental axial length (m)
P_w is wetted perimeter(m),
$\dot{m}$ is mass flow rate (kg/s) [$\dot{m}_1$=$\dot{m}_2$=$\dot{m}$]
q is heat flux (w/m^2)
T_w is wall temperature (^{0}C)
dQ is $qP_w dZ$ =heat load (W)
$\dot{m}$dS is rate of change in entropy (W/^{0}C)

According to Maxwell relation of thermodynamics, change in entropy can be represented in terms of enthalpy (h), pressure (P), temperature (T) and density (ρ) of the fluid as

$$dh = TdS + \frac{dP}{\rho} \tag{2}$$

$$dS = \frac{1}{T}\left(dh - \frac{dP}{\rho}\right) \tag{3}$$

Substituting equation (3) in equation (1)

$$dS_{gen} = \dot{m}\left(\frac{1}{T}dh - \frac{1}{T}\frac{dP}{\rho}\right) - \frac{dQ}{T_w} \tag{4}$$

$$dS_{gen} = \frac{\dot{m}}{T}(dh) - \frac{\dot{m}dP}{T\rho} - \frac{dQ}{T_w} \tag{5}$$

Rearranging equation (5)

$$\frac{dS_{gen}}{dZ} = \underbrace{\left\{\frac{\dot{m}}{T}\frac{dh}{dZ} - \frac{dQ}{T_w dZ}\right\}}_{1st} - \underbrace{\left\{\frac{\dot{m}}{T\rho}\frac{dP}{dz}\right\}}_{2nd} \tag{6}$$

1st term in L.H.S. i.e. in equation (6) represents contribution of heat transfer in entropy generation and 2nd term represents contribution of pressure drop in entropy generation.

1st term simplification is as follows:

$$\frac{\dot{m}}{T}\frac{dh}{dZ} - \frac{dQ}{T_w dZ} \tag{7}$$

$$\frac{1}{T}\frac{dQ}{dZ} - \frac{dQ}{T_w dZ} \tag{8}$$

Where $dQ = \dot{m}dh$

$$\frac{dQ}{dZ}\left(\frac{1}{T} - \frac{1}{T+\Delta T}\right) \tag{9}$$

Where $T_w = T + \Delta T$, ΔT is difference between wall temperature and bulk temperature.

$$\frac{dQ}{dZ}\left(\frac{\Delta T}{T^2(1+\Delta T/T)}\right) \tag{10}$$

Since $\frac{\Delta T}{T} \ll 1$ so it can be neglected.
Also, we can use $dQ = qdA = q.dZ.P_w$ and $q = h\Delta T$ in equation (10)

$$1\text{st term} \rightarrow \frac{q^2 P_w}{h' T^2} \tag{11}$$

Where P_w is wetted perimeter (m), h' is heat transfer coefficient ($W/m^{2\,0}C$).

2nd term simplification is as follows:

$$\frac{\dot{m}}{T\rho}\left(\frac{dP}{dz}\right) \tag{12}$$

$$2\text{nd term} \rightarrow \frac{1}{T}\frac{\dot{m}}{\rho}\left(\frac{fG^2}{2\rho D}\right) \tag{13}$$

Where G is mass flux (kg/m^2s)

Friction factor can be calculated by Filonenko correlation which is widely used [5,6] and is as follows

$$f = (1.82 logRe - 1.64)^{-2} \tag{14}$$

Substitute equation (13) and equation (11) in equation (6)

$$\frac{dS_{gen}}{dZ} = \frac{1}{T^2}\frac{q^2 P_w}{h'} + \frac{1}{T}\frac{\dot{m}}{\rho}\frac{fG^2}{2\rho D} \tag{15}$$

$$\frac{dS_{gen}}{dZ} dT = \frac{1}{T^2}\frac{q^2 P_w}{h'} dT + \frac{1}{T}\frac{\dot{m}}{\rho}\frac{fG^2}{2\rho D} dT \tag{16}$$

$$dS_{gen}\frac{dT}{dZ} = \frac{1}{T^2} dT \frac{q^2 P_w}{h'} + \frac{1}{T} dT \frac{\dot{m}}{\rho}\left(\frac{f\dot{G}^2}{2\rho D}\right) \tag{17}$$

$$Since\ T = T_{in} + \frac{QZ}{L\dot{m}c_p}; \frac{dT}{dZ} = 0 + \frac{Q(Tout - Tin)}{L\dot{m}c_p(Tout - Tin)} \rightarrow \frac{dT}{dZ} = \frac{(Tout - Tin)}{L} \tag{18}$$

Integrating equation, the total entropy generation rate (S_{gen}) can be obtained as

$$S_{gen} = \frac{L}{(Tout - Tin)}\left[\left(\frac{Tout - Tin}{ToutTin}\right)\frac{q^2 P_w}{h'} + \log\frac{Tout}{Tin}\left(\frac{1}{\rho}\right)\dot{m}\left(\frac{\dot{f}G^2}{2\rho D}\right)\right] \tag{19}$$

Equation (19) written in terms of calorimetric power, Nusselt number is as follows

$$S_{gen} = \frac{L}{(Tout - Tin)}\left[\left(\frac{Tout - Tin}{ToutTin}\right)\frac{4AQ^2}{L^2 {P_w}^2 NuK} + \log\frac{Tout}{Tin}\left(\frac{1}{\rho}\right)\dot{m}\left(\frac{\dot{f}G^2}{2\rho D}\right)\right] \tag{20}$$

Where K is the conductivity of fluid.

Nu number is calculated by Petukhov-Kirillov correlation [6]

$$Nu = \frac{\left(\frac{f}{8}\right)RePr}{1.07 + 12.7\left(Pr^{\frac{2}{3}} - 1\right)\sqrt{\left(\frac{f}{8}\right)}} \tag{21}$$

$$S_{gen} = \left[\left(\frac{1}{ToutTin}\right)\frac{4AQ^2}{LP_w{}^2NuK} + \frac{\log\frac{Tout}{Tin}}{(Tout-Tin)}\left(\frac{1}{\rho}\right)\dot{m}\,\frac{fG^2}{2\rho D}\right] \quad (22)$$

Generally, entropy generation is defined in terms of dimensionless number

$$\emptyset_{total} = \frac{S_{gen}}{Q/(T_{out}-T_{in})} \;, \emptyset_{heat} = \frac{S_{heat}}{Q/(T_{out}-T_{in})} \,, \emptyset_{pd} = \frac{S_{pd}}{Q/(T_{out}-T_{in})} \quad (23)$$

3 METHODOLOGY

For the evaluation of entropy generation given by equation (23), experimental data from two campaigns [7, 8] is used. The flow schematic of experimental High Heat Flux Test Facility namely (HHFTF) situated at Institute for Plasma Research, Gandhinagar, India is shown in Figure 3.

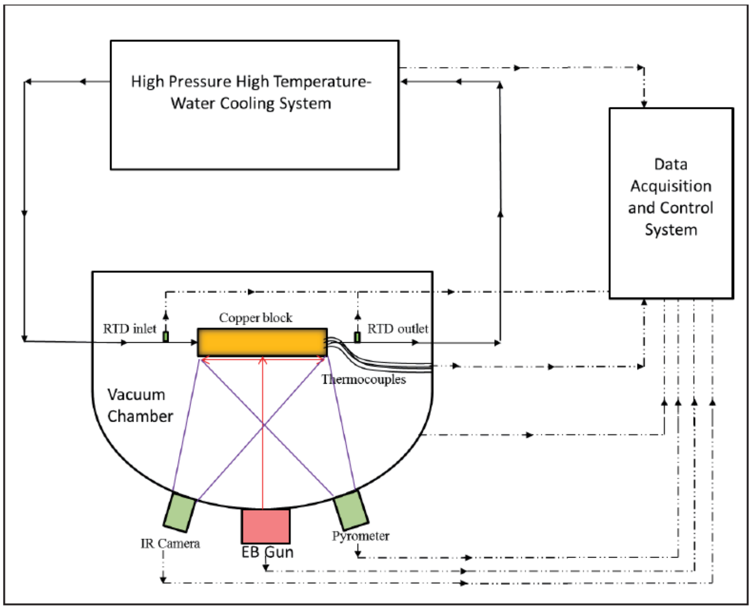


Figure 3: Flow schematic of High Heat Flux Test Facility.

HHFTF consists of High Pressure High Temperature Water Cooling System (HPHT-WCS), vacuum chambers, electron beam gun, data acquisition and control system. The HPHT-WCS is designed to provide and maintain the necessary temperature, pressure and flow rate of the cooling water to cool down plasma facing components/units being tested in HHFTF. HPHT-WCS can go up to 60 bar and 160 ^{0}C and deliver flow rate up to 300 lpm. Vacuum chamber can be maintained at a pressure of 10^{-5} mbar. Electron beam gun can produce 200 KW of energy that can be rastered on the surface of the test mockup. The Data acquisition and Control System (DACS) is developed to operate in local/remote and Auto/manual mode of operation. The diagnostics mainly consist of IR camera and Pyrometer which are used to measure the surface temperature. Thermocouples are used to measure the copper block temperature and Resistance Temperature Detector (RTD) sensor at inlet and outlet of test mockup (copper block) are used to measure the water temperature. Detailed information on the diagnostics used and their accuracy can be found in the previous study [8].

The smooth and swirl tube mockup for the study considered was a Copper block (CuCrZr). The cross section of smooth and swirl tube mockup are shown in Figure 4.

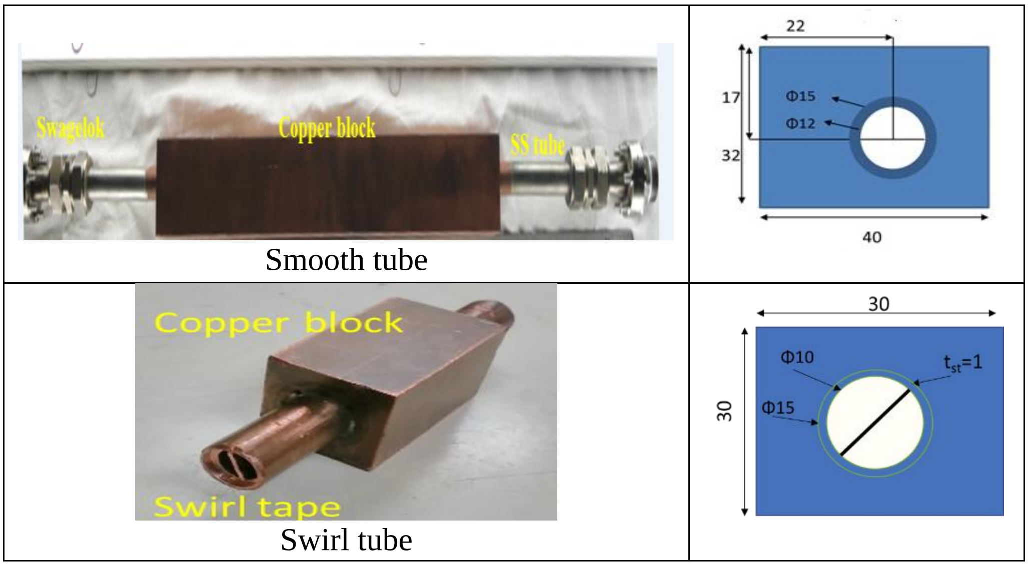


Figure 4: Test mockup

The smooth test mock-up has dimension 400 mm x 32mm x 40mm width and internal tube of 12 mm inner and 15 mm outer diameter whose centre is offset by 17×22 mm. The offset was added to study the effect of shape factors under one sided heating conditions, by performing tests on different faces of the copper block. The swirl tube test mock-up has a dimension 50mm x 30mm x 30mm. Tube part was machined by turning it from mock-up dimensions to the outer diameter dimensions of 15 mm while inside diameter was drilled with the dimensions of 10 mm. Swirl tape inserts were introduced in the flow path of the coolant inside the flow channel of copper tube. The tape introduced inside the flow channel was made of copper. The twist ratio of the tape was 3.5. Pitch of the swirl tape was 35 mm, width was 10 mm and thickness was 1 mm.

In the calorimetry experiment, the surface of the copper mono block was rastered with the help of the electron beam gun. The surface temperature was measured by using a pyrometer. The distribution of temperature on the surface was measured by IR camera. The inlet and outlet temperatures of the coolant flow were recorded by the set of RTDs situated at inlet and outlet of the Mock up. The difference between outlet and inlet temperature was found and the amount of power absorbed was calculated with the help of mass flow rate and the specific heat capacity at particular temperature for the fluid. Calorimetric power is calculated using RTD and flow meter data. The calorimetric power (in W) is estimated by the following formula.

$$Q = \dot{m} c_p \Delta T \tag{16}$$

Where $\dot{m}$ - mass flow rate (kg/s), C_p - Specific heat at constant pressure (J/kg °C) and ΔT =T_{out}-T_{inlet} -Temperature between outlet and inlet at steady state in (°C)

The range covered during experiments is shown in Table 1.

Table 1: Experimental matrix

Geometry	Pressure (bar)	Inlet temperature (°C)	Flow rate (lpm)	Beam power (kW)	Heated length (mm)
Smooth	3-10	30- 50	30 -100	15-73	100, 150, 200
Swirl	3-15	32-60	30-90	12-38	50

4 RESULTS

4.1 Effect of calorimetric power on entropy generation

The total entropy generation number (Φ total), heat transfer entropy generation number (Φ heat), and pressure drop entropy generation number (Φ pd) is plotted against calorimetric power for smooth tube as shown in Figure 5. The beam power is varied at a fixed volume flow rate (100 lpm), pressure (10 bar), inlet temperature (50 ^{0}C) and heated length (100 mm). The slight change in Reynolds number and Prandtl numbers are due to the mild variation of bulk temperature during the experiments.

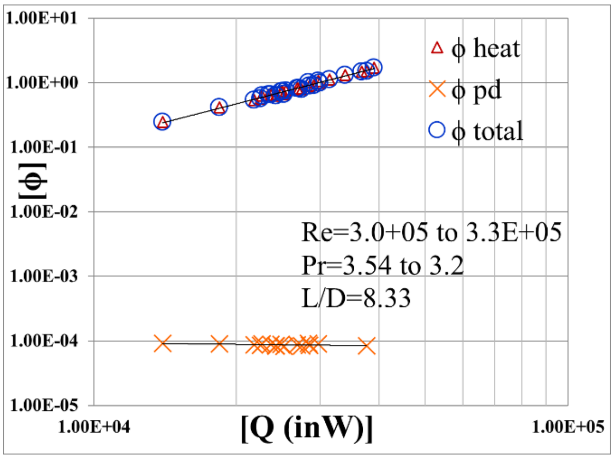
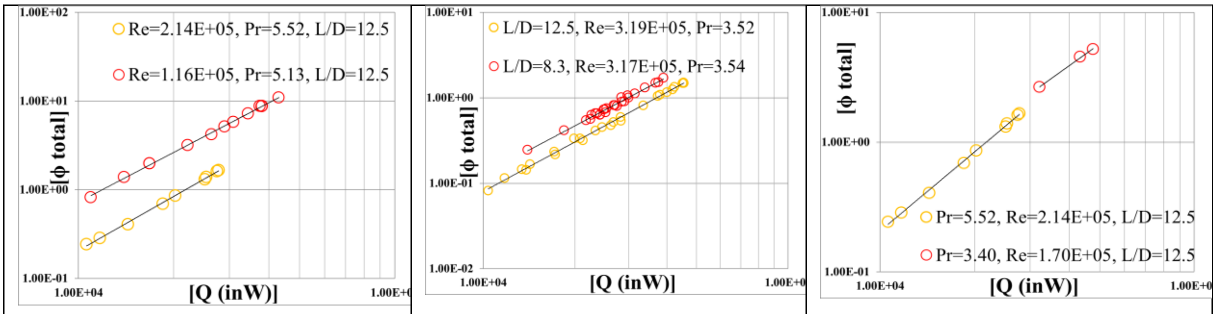


Figure 5: Entropy generation versus calorimetric power for smooth tube

The results show that total entropy generation increases with the increase in calorimetric power. Also, the contribution of heat transfer in total entropy generation is found to be much higher than the contribution of pressure drop.

4.2 Effect on variation of Reynolds number, Prandtl number and Heated length to Hydraulic diameter ratio on entropy generation:

The effect of Reynolds number, Prandtl number and heated length to hydraulic diameter ratio on entropy generation were analysed for smooth tube and is shown in Figure 6. The total entropy generation number (Φ total) is plotted against calorimetric power for three cases (Re, Pr, and L/D) with variation of one parameter and keeping the other two same to see individual effect of that parameter on entropy generation.



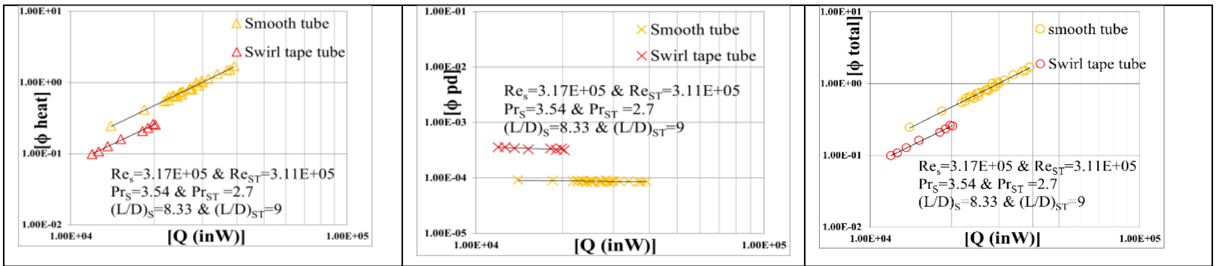
(a) Variation of Re	(b) Variation of (L/D)	(c) Variation of Pr

Figure 6: Effect of Re, Pr and (L/D) on entropy generation for smooth tube.

Figure 6 (a) shows the variation of Reynolds number keeping Prandtl number and heated length to hydraulic diameter ratio as same for both the Reynolds numbers (Re=2.14E+05 and Re=1.16E+05). The temperature variation during different experimental shots was maintained as less as possible to maintain similar dimensionless numbers (Pr= 5.52 & 5.13). Entropy generation is found to be lower for higher Reynolds number, as an increased heat transfer coefficient results in a lower wall to bulk temperature difference which lowers the entropy generation. Figure 6 (b) shows variation of a heated length to hydraulic diameter ratio while keeping the Prandtl number and Reynolds number the same. Entropy generation is found to be lower for higher heated length to hydraulic diameter ratio. Figure 6 (c) shows the variation of Prandtl number while keeping the Reynolds number and Heated length to Hydraulic diameter ratio the same. The increment in the Reynolds number (Re=2.14E+05 and Re=1.70E+05) is lower than the increment in Prandtl numbers (Pr=5.52 and 3.40) whereas L/D remains the same value of 12.5 for both Prandtl numbers. The contribution of the Prandtl number to the entropy generation is more dominant than the contribution of the Reynolds number (as shown in Figure 6 (c)). Entropy generation is found to be lower for higher Prandtl number as the higher Prandtl number increases the Nusselt number, hence lowers the entropy generation.

4.3 Comparison of Smooth tube versus Swirl tube

The total entropy generation number (Φ total), heat transfer entropy generation number (Φ heat), and pressure drop entropy generation number (Φ pd) is plotted against calorimetric power for both smooth tube and swirl tube as shown in Figure 7.



(a) Entropy generation due to Heat transfer	(b) Entropy generation due to pressure drop	(c) Total entropy generation

Figure 7: Comparison of smooth and swirl tube

Figure 7 (a) shows comparison of entropy generation due to heat transfer for smooth and swirl tube. The increment in Reynolds number, L/D for smooth tube (Re_S=3.17E+05, $(L/D)_S$ =8.33) and swirl tube Re_{ST}=3.11E+05, $(L/D)_{ST}$ =9) is less compared to increment in Prandtl number for smooth tube (Pr_S=3.54) and swirl tube (Pr_{ST}=2.7). The entropy generation due to the heat transfer for swirl tube is found to be lower than for the smooth tube, as swirl enhances heat transfer coefficient for same calorimetric power, which reduces the entropy generation. It must be noted that swirl tube performance is better than smooth tube even though the Prandtl number for the smooth tube is higher than in the case of swirl tube; as heat transfer in swirl tube is dominant as compared to smooth tube. Figure 7 (b) shows comparison of entropy generation due to pressure drop for smooth and swirl tube. The entropy generation due to pressure drop for swirl tube is found to be higher than smooth tube as swirl enhances frictional pressure drop, which increases the entropy generation. Figure 7 (c) shows the comparison of total entropy generation for smooth and swirl tube. The total entropy generation for swirl tube is found to be lower than smooth tube because heat transfer contribution is much more than pressure drop contribution in the total entropy generation. The entropy generation due to heat transfer is lower for the swirl tube, hence total entropy generation is also lower, showing that the swirl tube has better performance over the smooth tube and although the pressure drop is higher as compared to the smooth tube

5 CONCLUSION AND FUTURE WORK

A study has been performed to evaluate and compare the entropy generation of smooth and swirl tube geometries of ITER like divertor in a single-phase flow condition. Also, the effects of Reynolds number, Prandtl Number and Heated length to hydraulic diameter ratio on entropy generation were analysed. The main findings are as follows:

1. Total entropy generation increases with the increase in calorimetric power.
2. The contribution of heat transfer in total entropy generation is found to be much higher than the contribution of pressure drop.
3. An increase in Reynold number, Prandtl number, or Heated length to Hydraulic diameter ratio will decrease entropy generation and results in better performance.
4. Swirl tube has better performance over the smooth tube, even though the pressure drop is higher as compared to smooth tube.

In the future work, more experiments will be performed specifically for entropy generation in smooth and swirl tube geometries of ITER like divertor. Also, a CFD study will be performed to investigate the distribution of entropy generation in these geometries.

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