Exergy analysis of turbulent flow for tubes of power plant feed water heaters and condensers

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Abstract: The thermal performance of heat exchangers that are essential units in power plants can be substantially improved by a number of augmentation techniques. The entropy generation and exergy destruction rate due to the flow friction and heat transfer across temperature differences were proposed numerically to evaluate the benefits of utilisation of these techniques. Enhanced tubes with either dimples or spiral corrugations that are isothermally heated were investigated. The combination of spirally corrugated tubes with twisted tape inserts was also presented. In general, dimpled and spirally corrugated tubes and the combination of spirally corrugated tubes with a twisted tape substantially increase the percentage of temperature raise ratio and decrease the percentage of exergy destruction rate relative to smooth tubes. Increasing both the additional heat transfer area due to dimpling, and ridge height of corrugation increases the percentage of temperature raise ratio and decreases the exergy destruction rate. Also, the combination of corrugated tubes with twisted tapes is attractive as an augmentation technique based on exergy analysis, especially at low twisted tape length to inner tube diameter ratio, and high ridge height of corrugation for high Reynolds number.

Keywords: forced convection; exergy; dimpled and spirally corrugated tubes; twisted tape inserts.

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1 Introduction

In recent years, exergy analysis has a wide range of applications and has become a thermo-economics concept. The exergy analysis of power plants aims to investigate the influence of every component in the system on the overall efficiency and tries to eliminate processes in the power system that diminish its performance. Also, the exergy analysis of power plant processes allows identification of methods for improving system effectiveness. The quantitative exergy analysis presented by Verkhivler and Kosoy (2001) for power plants indicated that dominating irreversibilities are associated with the combustion process and the heat transfer in heat exchangers through a temperature difference. This study showed that the exergy destruction rate reaches 5.32% owing to the heat transfer in condensers, net heaters and feed water heaters.

The exergy destruction due to entropy generation is mainly due to the irreversible nature of heat transfer across a temperature difference and the friction flow accompanied with the augmentation techniques. Therefore, it is essential to understand how entropy is being generated in convective heat transfer processes. Bejan (1980, 1982), Bejan and Pfister (1980) and San et al. (1987) analysed the entropy generation based on the aspects of 2nd law of thermodynamics for convective heat transfer. Sahin (1998) developed a theoretical model based on the exergy concept to predict the entropy generation for a fully developed laminar flow in a duct subjected to a constant wall temperature. Abdel-Moneim (2002) presented an evaluation of the augmentation heat transfer techniques based on their impact on entropy generation. His study showed that there are optimum Reynolds numbers of minimum exergy destruction rate which depend on both the heat flux and augmentation technique. The present study aims to evaluate the performance of heaters used to elevate the outlet feed water temperature in power plants, based on exergy analysis. The proposed evaluation is applied to the heat transfer enhancement technique using dimpled tubes discussed by Chen et al. (2001) and spirally corrugated tubes presented by Dong et al. (2001) and Zimparov et al. (1991). Also, the present study was extended to evaluate the insertion of twisted tapes inside spirally corrugated tubes presented by Zimparov (2001). The present study aims to provide the designers concerned in heat exchangers used in power generating systems with knowledge of the thermodynamic impact of entropy generation and exergy destruction.

2 Theoretical model and method of calculation

The entropy generation accompanied by convective heat transfer through an isothermally heated tube, shown in Figure 1, can be evaluated using equation (1), presented by Abdel-Moneim and Ali (2006, 2007).

$$\mathrm{d}\dot{S} = \left(\frac{\tau^2 hw}{\tau+1}\right)\mathrm{d}x - \frac{\dot{m}}{\rho T}\left(\frac{\mathrm{d}p}{\mathrm{d}x}\right)\mathrm{d}x \tag{1}$$

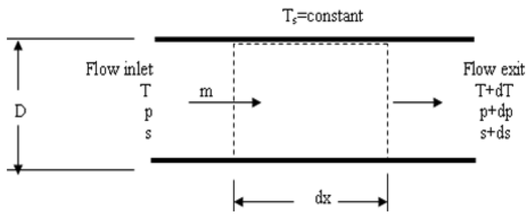
where the 1st term of the right-hand side of equation (1) represents the entropy generation rate due to heat transfer across a finite temperature difference while the 2nd term represents the contribution of the flow friction in entropy production. On substituting the dimensionless parameters, equation (1) can be transformed into dimensionless form as:

$$\mathrm{d}\sigma = \left(\frac{\tau^2}{\tau+1}\right) \mathrm{Nu}\ \xi\ \mathrm{d}\chi + 2\frac{\mathrm{SBr}}{\mathrm{Pr}} F\ \mathrm{d}\chi. \tag{2}$$

The net entropy generation rate $\dot{S}$ can be obtained after integrating equation (2) along the entire length of the tube,

$$\dot{S} = \sigma \, \dot{m} \, c_p. \tag{3}$$

Figure 1 Control volume in a tube subjected to a uniform surface temperature



Also, the percentage exergy destruction rate associated with the heat transfer process along the duct can be calculated by,

$$\Psi\% = \frac{T_0 \dot{S}}{\dot{Q}_{\text{in}}} \times 100 \tag{4}$$

where, T_o is the reference temperature in the thermodynamic scale, K.

The integration of equation (2) requires either measurements or theoretical knowledge about the characteristics of both the heat transfer in terms of Nu and the flow friction in terms of F. In the case where the heat transfer and flow measurements are available the integration of equation (2) can be accomplished according to the following stepwise procedure:

1 The heat flux along the tube surface, $q(x) = h\,\Delta T_s(x)$, can be calculated with the aid of the tube surface and inlet flow temperatures and the heat transfer characteristics in terms of Nu, presented by Chen et al. (2001), Dong et. al. (2001), Zimparov et al. (1991) and Zimparov (2001).

2 With the knowledge of heat flux, $q(x)$, mass flow rate ($\dot{m}$) and inlet flow temperature (T_i), the increase in flow bulk temperature can be calculated,

$$\Delta T_b = \frac{q(x)\pi D \Delta x}{\dot{m} c_p}.$$

3 The pressure distribution along the duct can be obtained from the fluid flow characteristics presented by Chen et al. (2001), Dong et. al. (2001), Zimparov et al. (1991) and Zimparov (2001).

4 The results of steps (1–3), the local values of the dimensionless terms τ, χ, ξ, SBr, F and Nu can be calculated while Pr can be found at the flow bulk temperature.

5 By integration of equation (2) along the tube length, the dimensionless term, σ, can be calculated and, consequently, the net entropy generation rate, $\dot{S}$, from equation (3).

Finally, the percentage of exergy destruction rate, $\Psi\%$, can be found by substituting with S from equation (3) into equation (4).

3 Results and discussion

Dimpled and spirally corrugated tubes are widely applied in heat extraction and recovery systems in power plants in a turbulent flow condition. Therefore, in addition to the case of the smooth tube, dimpled and spirally corrugated tubes with tape inserts are evaluated based on exergy analysis using the present performance evaluation criterion. Dimpled tubes with different configurations, shown in Figure 2 and Table 1 presented by Chen et al. (2001) was evaluated for isothermal heating turbulent flow ($4000 < Re_D < 55,000$). Spirally corrugated tubes tested by Dong et al. (2001) (Figure 3 and Table 2) in the range of Reynolds number 3000–81,000 and Zimparov et al. (1991) (Figure 4 and Table 3) in the range of Reynolds number $10 \times 10^3 - 70 \times 10^3$ were studied. Also, the effect of inserting twisted tape inside spirally corrugated tubes presented by Zimparov (2001) in the range of Reynolds number $3 \times 10^3 - 70 \times 10^3$ based on the exergy destruction rate was performed. The characteristics of tubes presented by Zimparov (2001) are shown in Table 4. The percentages of exergy destruction rate and temperature raise ratio for dimpled tubes are shown in Figure 5 in the range of Reynolds number from 4×10^3 to 55×10^3. For a fixed Reynolds number, the effect of dimpling substantially increases the temperature raise ratio, $\Delta T/T\%$, and decreases the exergy destruction rate, $\Psi\%$. This is due to the augmentation in heat transfer rate that decreases the difference between the surface and the flow bulk temperatures and, consequently, the resulting irreversibility. For $Re_D > 30,000$, an increase of 29–120% in the percentage of temperature raise ratio, γ, and a reduction of 11.9–22% in the percentage of exergy destruction rate, β, relative to smooth tubes are obtained. From Figure 5, it can be concluded that increasing the additional heat transfer area due to the dimpling (highest dimple effect in tube 4) decreases the exergy destruction rate and elevates the outlet feed water temperature. A plot of exergy destruction rate and the temperature raise ratio vs. Reynolds number for spirally corrugated tubes tested by Dong et al. (2001) is presented in Figure 6. There is an obvious increase in γ of 50%, and reduction in β of 10% for spirally corrugated tubes relative to smooth tubes for high Reynolds number, $Re_D > 30,000$. Also, the predication of the exergy destruction rate and the temperature raise ratio for different configurations of spirally corrugated tubes presented by Zimparov et al. (1991) are listed in Table 5. It is shown that the corrugation process enhances the percentage temperature raise ratio, $\Delta T/T\%$, and decreases the percentage exergy destruction rate, $\Psi\%$, where there is 100% enhancement in γ and 10% average reduction in β for the illustrated types of corrugated tubes relative to smooth tubes. Figures 7 and 8 show the exergy destruction rate and the temperature raise ratio for spirally corrugated tubes with twisted tape presented by Zimparov (2001). It is clear that applying corrugated tubes with twisted tape in heat exchangers increases the percentage temperature raise ratio, $\Delta T/T\%$, and decreases the percentage exergy destruction rate, $\Psi\%$. An increase of 75–100% in γ and 20–25% reduction in β are obtained in the case of empty corrugated tubes for $Re_D > 30,000$. Insertion of twisted tape inside corrugated tubes substantially enhances the percentage temperature raise ratio, $\Delta T/T\%$, and decreases the percentage exergy destruction rate, $\Psi\%$, as shown in Figures 7 and 8. As can be seen, decreasing H/D of the inserted twisted tape enhances the percentage temperature raise ratio and decreases the percentage exergy destruction rate. This may be attributed to the increase in the level of swirl flow owing to the insertion of twisted tape. An increase of 130–300% in γ and a reduction of 25–55% in β are obtained. It is observed that increasing the ridge height of corrugation enhances the temperature raise temperature ratio and reduces the exergy destruction rate. This may be returned to the increase in turbulence level with the increase in the ridge height of corrugation. Table 6 summarises the performance of all augmentation techniques relative to smooth tubes under the shown conditions. In general, dimpled and spirally corrugated tubes and the combination of spirally corrugated tubes with a twisted tape substantially increase the percentage of temperature raise ratio and decrease the percentage of exergy destruction rate relative to smooth tubes. From Table 6, it can be concluded that the combination of corrugated tubes with twisted tapes is more attractive, especially at low *H*/*D* and high ridge height of corrugation for high Reynolds number.

Figure 2 Sketch of dimple tube ($N = 4$) presented by Chen et al. (2001)

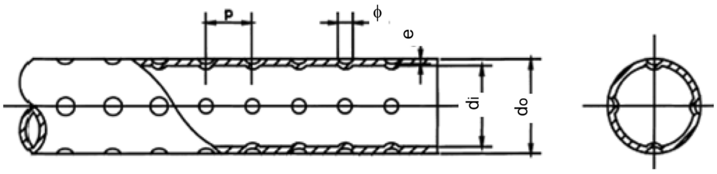


Table 1 Characteristic dimensions of dimpled tubes presented by Chen et al. (2001)

Physical quantity	*Smooth tube*	*Dimple tubes*					
	Tube 0	*Tube 1*	*Tube 2*	*Tube 3*	*Tube 4*	*Tube 5*	*Tube 6*
a, mm^2	0	1510.6	2756.3	769	4307.6	1265.2	465.8
di, mm	16.6	16.6	16.6	16.6	16.6	16.6	16.6
ä, mm	1.22	1.22	1.22	1.22	1.22	1.22	1.22
L, mm	1500	1500	1500	1500	1500	1500	1500
e, mm		1.2	1.5	0.5	1.3	0.7	0.6
ö, mm		4.5	3	2	3.5	4.7	5.5
p		12	14	8	10	10	10
N		3	4	6	6	6	3
e/*d*		0.0723	0.0904	0.0301	0.0783	0.0422	0.0362
e/*p*		0.1	0.1071	0.0625	0.13	0.07	0.06
a/*A*		0.0174	0.0318	0.0089	0.0496	0.146	0.0054

$a = N[(1500 - 150)/p]\,[(\phi/2)^2+e^2]\pi$; $A = \pi L(d_i + \delta)$; *N*: number of dimple rows on tube surface; *L* = Tube length.

Figure 3 Sketch of the test with spirally corrugated surfaces presented by Dong et al. (2001)

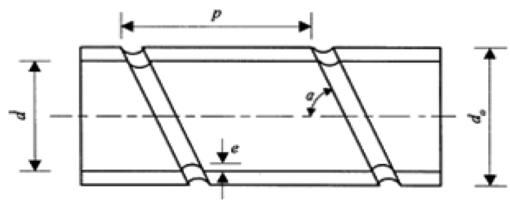
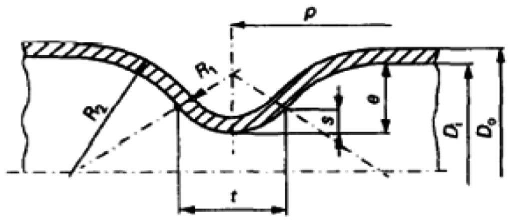


Table 2 Dimensions of the four spirally corrugated tubes presented by Dong et al. (2001)

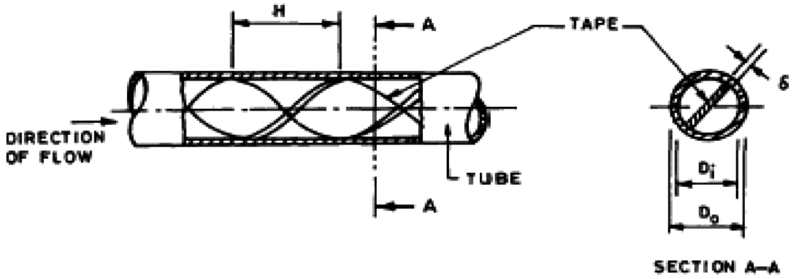
Tube no.	D_o (mm)	D_i (mm)	*e* (mm)	*p* (mm)	e/D_i	p/D_i	α (*deg*)	*L* (mm)
1	19	16.04	0.39	10	0.0243	0.623	78.8	1800
2	19	16.12	0.32	10	0.0199	62	78.8	1800
3	25	22.82	0.69	10	0.0302	438	82.1	1800
4	25	20.08	0.8	12	0.0398	0.598	79.2	1800

α: Helix angle; *e*: roughness height; *L*: Tube length.

Figure 4 Sketch of spirally corrugated tubes studied by Zimparov et al. (1991) and Zimparov (2001) (a) empty spirally corrugated tubes and (b) spirally corrugated tube with twisted tape



(a)



(b)

Table 3 Characteristics of spirally corrugated tubes studied by Zimparov et al. (1991)

Tube no.	*Do* (mm)	*Di* (mm)	*e* (mm)	*p* (mm)	*t*(mm)	*s* (mm)	β (*deg*)	*N* (*starts*)
11	27.4	25.25	0.808	14.47	2.69	0.327	80.5	1
12	27.46	25.43	0.818	14.42	2.77	0.29	80.5	1
13	27.27	25.22	0.833	12.41	2.39	0.26	81.8	1
14	27.25	25.19	0.805	10.74	2.65	0.3	82.8	1
15	27.37	25.31	0.757	10.14	2.6	0.333	83.3	1
16	27.4	25.42	0.759	8.64	2.61	0.334	84.3	1
17	27.19	25.18	0.984	14.47	2.67	0.388	80.4	1
21	27.2	26.06	0.876	14.46	2.79	0.347	80.4	1
22	27.59	25.44	0.823	14.32	2.87	0.307	80.6	1
23	27.17	25.15	0.869	12.35	2.98	0.39	81.8	1

Table 3 Characteristics of spirally corrugated tubes studied by Zimparov et al. (1991) (continued)

Tube no.	*Do* (mm)	*Di* (mm)	*e* (mm)	*p* (mm)	*t*(mm)	*s* (mm)	β (*deg*)	*N* (*starts*)
24	27.1	25	0.75	10.64	2.77	0.289	82.9	1
25	27.43	25.4	0.763	10.05	2.71	0.327	83.3	1
26	27.47	25.34	0.706	0.865	2.46	0.281	84.3	1
27	27.19	25.14	0.972	14.34	3.22	0.446	80.5	1
18	27.27	25.2	1.022	10.95	2.65	0.379	82.7	1
19	27.35	25.27	1.071	16.85	3	0.487	78.9	1
28	27.23	25.26	0.979	10.96	2.91	0.415	82.7	1
29	27.5	25.48	1.018	16.85	2.89	0.366	79	1
31	27.33	25.4	0.71	6.49	2.19	0.34	85.7	1
32	27.11	24.97	0.943	7.9	2.79	0.463	84.7	1
33	27.56	25.62	0.447	6.55	2.18	0.222	85.7	1
34	27.62	25.78	0.628	8.48	2.46	0.3	84.4	1
35	26.95	24.9	1.165	14.2	2.95	0.463	80.5	1
51	27.88	25.77	1.175	10.52	2.19	0.239	70.2	3
52	27.59	25.53	0.903	8.63	2.32	0.25	73.4	3

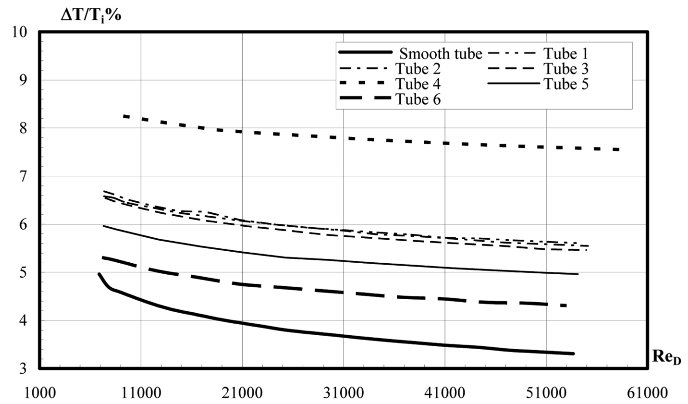
t: Cap width of ridge; *e*: Height of ridge; β: Spiral angle of the ridge with respect to the axis.

Table 4 Dimensions of three-start spirally corrugated tubes presented by Zimparov (2001)

Tube no.	*Do* (mm)	*Di* (mm)	*e* (mm)	*p* (mm)	β (*deg*)	*e*/*Di*	*P*/*e*	β*	*H*/*Di*
4040	15.72	13.68	0.557	5.97	67.4	0.0407	10.73	0.749	empty
4041	15.72	13.68	0.557	5.97	67.4	0.0407	10.73	0.749	15.4
4042	15.72	13.68	0.557	5.97	67.4	0.0407	10.73	0.749	12.3
4043	15.72	13.68	0.557	5.97	67.4	0.0407	10.73	0.749	7.8
4044	15.72	13.68	0.557	5.97	67.4	0.0407	10.73	0.749	5.9
4045	15.72	13.68	0.557	5.97	67.4	0.0407	10.73	0.749	4.8
4030	15.72	13.73	0.781	5.82	68	0.0569	7.45	0.755	empty
4031	15.72	13.73	0.781	5.82	68	0.0569	7.45	0.755	15.3
4032	15.72	13.73	0.781	5.82	68	0.0569	7.45	0.755	12.2
4033	15.72	13.73	0.781	5.82	68	0.0569	7.45	0.755	7.7
4034	15.72	13.73	0.781	5.82	68	0.0569	7.45	0.755	5.8
4035	15.72	13.73	0.781	5.82	68	0.0569	7.45	0.755	4.7

β: Heix angle; $\beta^* = \beta/90$; *H*: Length of twisted tap in 360°; *p* and *e* are shown in Figure 4.

Figure 5 Percentage of feed water temperature raise ratio and exergy destruction rate for dimpled tubes presented by Chen et al. (2001) at $T_s = 328.8$ K, $T_o = 298$ K and $T_i = 290.1$ K. (a) Percentage of feed water temperature raise ratio and (b) Percentage of exergy destruction rate



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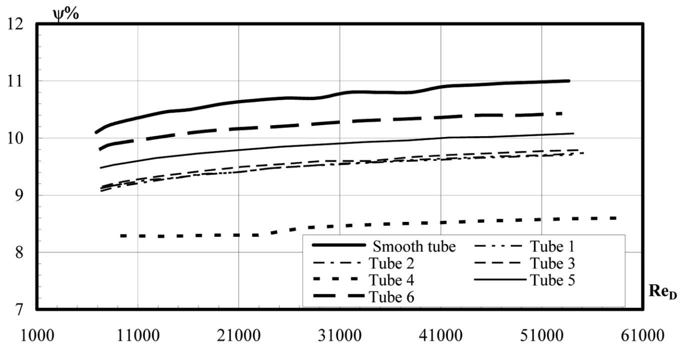

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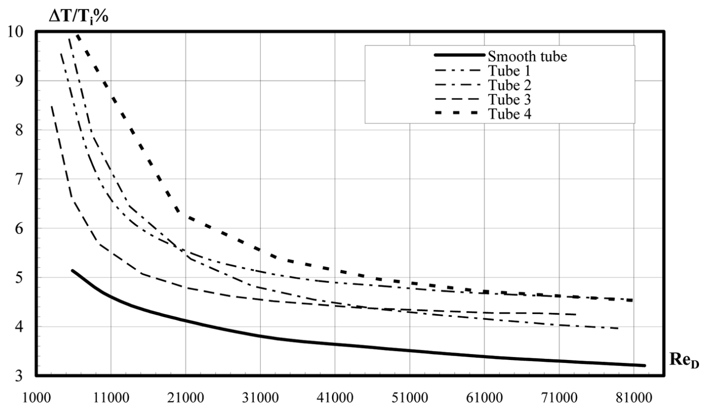
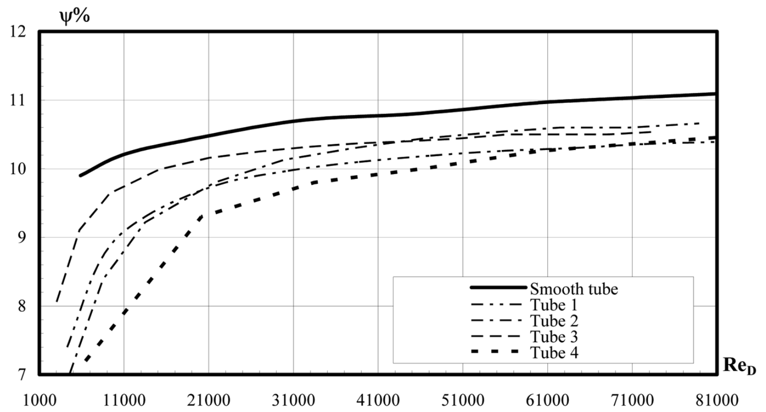
Figure 6 Percentage of feed water temperature raise ratio and exergy destruction rate for spirally corrugated tubes presented by Dong et al. (2001) at $T_s = 328.8$ K, $T_o = 298$ K and $T_i = 290.1$ K. (a) Percentage of feed water temperature raise ratio and (b) Percentage of exergy destruction rate



(a)

Figure 6 Percentage of feed water temperature raise ratio and exergy destruction rate for spirally corrugated tubes presented by Dong et al. (2001) at T_s = 328.8 K, T_o = 298 K and T_i = 290.1 K. (a) Percentage of feed water temperature raise ratio and (b) Percentage of exergy destruction rate (continued)

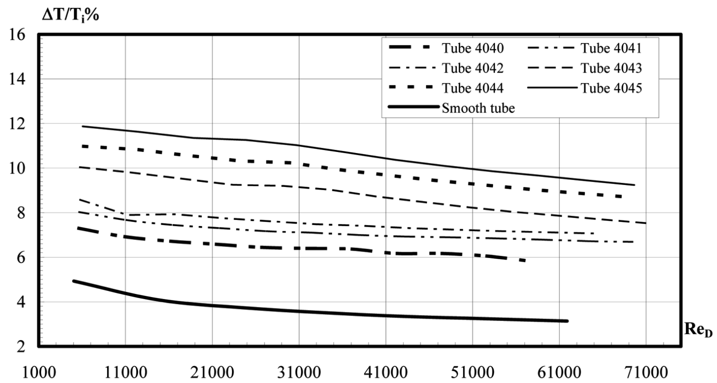


(b)

Table 5 Percentage of feed water temperature raise ratio and exergy destruction rate for spirally corrugated tubes studied by Zimparov et al. (1991) at T_s = 328.8 K, T_o = 298 K and T_i = 290.1 K

Tube no.	Re_D	ψ (%)	$\Delta T/T$ (%)	*Tube no.*	Re_D	ψ (%)	$\Delta T/T$ (%)
11	10239–70080	9.38–10.4	6.13–4.3	18	10395–70323	9.2–10.1	6.6–4.9
12	10000–70363	9.66–10.5	5.61–4.13	19	10310–69930	9.3–10.5	6.4–4.2
13	10215–70350	9.44–10.2	6.03–4.55	28	10286–70232	9.2–10.3	6.3–4.6
14	10228–69912	9.44–10.2	6.03–4.55	29	10123–69347	9.4–10.3	6.1–4.4
15	10073–69971	9.6–10.3	5.68–4.51	31	10025–69873	9.6–10.3	5.5–4.6
16	10002–70525	9.38–10.4	5.87–4.65	32	10496–69708	9.1–9.9	6.6–5.17
17	10304–69868	9.3–10.5	6.25–4.06	33	9390–70082	10.6–10.8	3.9–3.6
21	9912–69552	9.4–10.4	6.1–4.3	34	9595–70502	10.2–10.4	4.8–3.4
22	9960–69188	9.7–10.4	5.5–4.3	35	10509–71495	9.2–10.2	6.5–4.7
23	10194–70398	9.5–10.2	5.9–4.7	51	9835–69853	9.7–10.7	5.6–4
24	10255–70025	9.5–10.3	5.9–4.5	52	10008–69748	9.5–11	5.8–3.3
25	9955–69853	9.5–10.5	5.8–4.6	Smooth	8995–66192	11.4–11.9	2.4–1.7
26	10092–70293	9.6–10.4	5.8–4.6				
27	10036–70674	9.2–10.3	6.4–4.6				

Figure 7 Percentage of feed water temperature raise ratio and exergy destruction rate for a three-start spirally corrugated tubes (ridge height = 0.557 mm) with twisted tape presented by Zimparov (2001) at T_s = 328.8 K, T_o = 298 K and T_i = 2901 K. (a) Percentage of feed water temperature raise ratio and (b) Percentage of exergy destruction ratio



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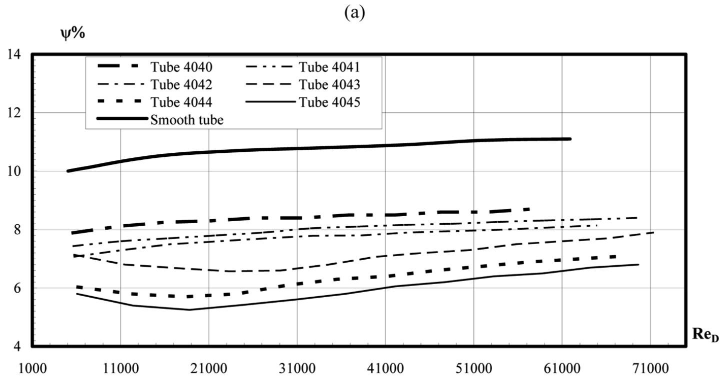
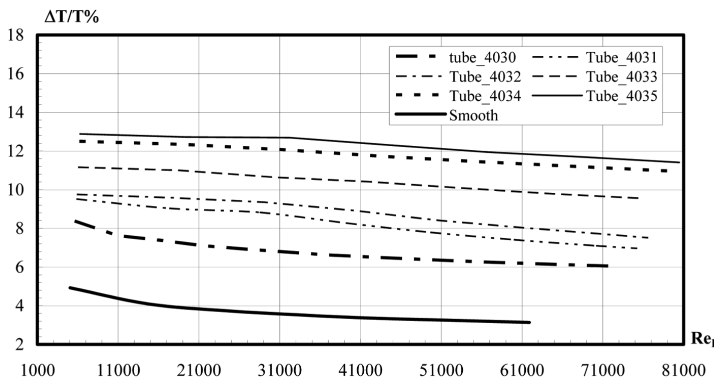


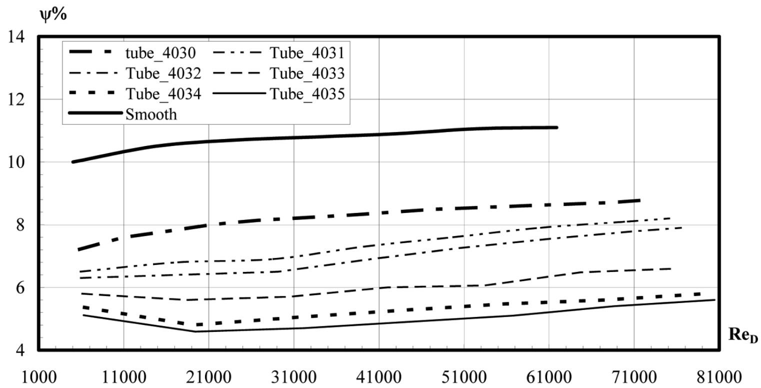
(b)

Figure 8 Percentage of feed water temperature raise ratio and exergy destruction rate for a three-start spirally corrugated tubes (ridge height = 0.781 mm) with twisted tape presented by Zimparov (2001) at T_s = 328.8 K, T_o = 298 K and T_i = 2901 K. (a) Percentage of feed water temperature raise ratio and (b) Percentage of exergy destruction ratio



(a)

Figure 8 Percentage of feed water temperature raise ratio and exergy destruction rate for a three-start spirally corrugated tubes (ridge height = 0.781 mm) with twisted tape presented by Zimparov (2001) at T_s = 328.8 K, T_o = 298 K and T_i = 2901 K. (a) Percentage of feed water temperature raise ratio and (b) Percentage of exergy destruction ratio (continued)



(b)

Table 6 Percentage of feed water temperature raise ratio and exergy destruction rate for different discussed tubes at T_s = 328.8 K, T_o = 298 K and T_i = 290.1 K

Type of enhancement	γ(%)	β(%)
Dimp led tubes tested by Chen et al. (2001)	29–120	12–22
Spirally corrugated tubes tested by Dong et al. (2001)	50	10
Spirally corrugated tubes tested by Zimparov et al. (1991)	100	10
Tubes tested by Zimparov (2001)		
Spirally corrugated tubes alone with ridge height = 0.781 mm	100	25
Spirally corrugated tubes alone with ridge height = 0.557 mm	75	20
Spirally corrugated tubes with twisted tape (ridge height = 0.781 mm)	150–300	25–55
Spirally corrugated tubes with twisted tape (ridge height = 0.557 mm)	130–230	25–50

4 Conclusions

Numerical investigation of dimpled tubes, spirally corrugated tubes and the combination of spirally corrugated tubes with twisted tapes used as heat transfer augmentation techniques in feed water heaters and condensers have been carried out. The following conclusions can be drawn based on the exergy performance:

- In general, dimpled tubes, spirally corrugated tubes and the combination of spirally corrugated tubes with twisted tapes, used as heat transfer augmentation techniques, substantially increase the temperature raise ratio and decrease the exergy destruction rate.
- Increasing the additional heat transfer area due to the dimpling of tube surface decreases the exergy destruction rate and increases the temperature raise ratio of the outlet feed water.

- The increase in the ridge height of corrugation enhances the temperature raise temperature ration and reduces the exergy destruction rate.
- The combination of corrugated tubes and twisted tapes is attractive as an augmentation technique based on exergy analysis, especially at low *H*/*D* and high ridge height of corrugation for high Reynolds number, $Re_D > 30{,}000$.
- It is necessary to evaluate the thermal performance of heat exchangers applied in heat extraction and recovery systems in power plants based on the 2nd law of thermodynamics.

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Nomenclature

Symbols	
c_p	Specific heat at constant p, J/kg.K
D	Tube inner diameter, m
h	Heat transfer coefficient, W/m^2.K
H	Length of twisted tape in 360^o
k	Thermal conductivity, W/m.K
L	Tube length, m
$\dot{m}$	Fluid mass flow rate, kg/s
P	Flow pressure, Pa
Q	Heat flux, W/m^2
$\dot{Q}$	Heat transfer rate, W
S	Specific entropy, J/kg.K
S	Entropy, J/K
$\dot{S}$	Entropy generation rate, W/K
T	Temperature, K
U	Flow velocity, m/s
w	Wetted perimeter, m
X	Axial distance, m
Subscripts	
b	Refers to the flow bulk temperature
D	Inner diameter
e	At exit
f	Fluid
i	At inlet
in	Refers to total heat input
m	Mean value
o	Reference value (at 298 K)
p	Constant pressure
s	Refers to tube surface temperature
w	At tube wall
Greek letters	
α	Fluid thermal diffusivity, m^2 /s
δ	Twisted tape thickness, m
Ψ%	Percentage exergy destruction rate
μ	Dynamic viscosity, kg/m.s
ρ	Density, kg/m^3
v	Fluid kinematic viscosity, m^2 /s
Δ	Difference value

Dimensionless terms	
F	Fanning friction factor, $F = (-\mathrm{d}p/\mathrm{d}x)D/2\rho U_m^2$
Nu	Nessult number, Nu = hD/k_f
Pr	Prandtl number, Pr = ν/α
Re_D	Reynolds number based on the plain tube diameter, $\mathrm{Re}_D = \rho U_m D/\mu$
SBr	Pseudo Brinkman number, SBr = $\mu U_m^2/kT$
β	Percentage of exergy destruction rate relative to smooth tube, $\beta\,\% = (\psi\,\%\ \text{augmented} - \psi\,\%\ \text{smooth}) \times 100/\psi\,\%\ \text{smooth}$
χ	Length scale, $\chi = x/D$
γ	Percentage of temperature raise ratio of heater relative to smooth tube, $\gamma\,\% = (\Delta T/T_i\ \text{augmented} - \Delta T/T_i\ \text{smooth}) \times 100/(\Delta T/T_i\ \text{smooth})$
σ	Dimensionless entropy generation (entropy generation rate to thermal capacity ratio), $\sigma = \dot{S}/\dot{m}c_p$
τ	Temperature difference number, $\tau = \Delta T/T = (Tw - T)/T$
ξ	Flow parameter, $\xi = wk/\dot{m}c_p$, and for pipe flow ξ = 4/ReD.Pr