Effect of surface roughness on the performance of heat exchanger

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Abstract

In this research work, double-pipe counter flow heat exchanger has been analyzed with various roughnesses of steel, aluminum and copper pipes and also with two different cold fluids: water and ammonia at same flow rates. Dimensions of the heat exchanger are inner and outer diameters of inner pipe being 0.034 and 0.042 m, whereas diameters of outer pipe are 0.054 and 0.06 m, respectively, and length of heat exchanger is 1.8 m. In K- ϵ modeling, computational fluid dynamics tool has been used for performance analyses and this computational work has been validated by entropy, exergy and entransy analyses. After computational numerical analyses, this investigation has concluded that maximum rate of heat transfer through heat exchanger has been found with copper–ammonia combination with smooth surface. Minimum rates of entropy generation, exergy destruction, entransy dissipation-based thermal resistance and entransy dissipation number have been obtained with copper–water combination, and minimum entropy generation number and maximum effectiveness have been obtained with copper–ammonia combination. Percentage changes in the parameters/properties have also been calculated at different operating conditions. Copper as inner pipe material with smooth surface and ammonia as cold fluid have been recommended for counter flow double-pipe heat exchanger. Computer software has been developed for hassle-free analyses of heat exchanger.

Keywords Entropy analyses · Exergy analyses · Entransy analyses · Surface roughness · Double-pipe counter flow heat exchanger

List of symbols

C_p	Specific heat of flowing fluids (kJ/kg-K)
G	Entransy (kW-K)
m	Mass flow rate of fluid (kg/s)
T	Temperature (K)
S	Entropy (kW/K)

Abbreviations

d	Dissipation
f	Flowing fluid

Greek words

φ_{des}	Exergy destruction rate (kW)
ϵ	Effectiveness

1 Introduction

In a heat exchanger, heat is transferred from hot fluid to cold fluid by conductive and convective heat transfer mechanisms. The hot or cold fluid is separated through solid walls called pipes to avoid mixing of fluid or direct contact. Shell- and tube-type heat exchanger, double-pipe heat exchanger and plate- or fin-type heat exchanger are different types of heat exchangers mainly used in various industries like power plants, chemical plants, refrigeration and air-conditioning systems [1–4]. Double-pipe counter flow heat exchanger (as shown in Fig. 1) has been chosen for CFD analyses and found effectiveness, overall heat transfer coefficient and outlet temperatures of the flowing fluids for different cases [5], and then numerical validation has been done by analyzing the rates of entropy generation, exergy destruction and entransy dissipation. The

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Fig. 1 Double-pipe counter flow heat exchanger

Table 1 Dimensions of double-pipe heat exchanger

Sr. no.	Pipe	Inner diameter (mm)	Outer diameter (mm)	Length (mm)
1	Inner pipe	34	42	1800
2	Outer pipe	54	60	1800

dimensions of double-pipe counter flow heat exchanger chosen in this research are shown in Table 1. Double-pipe counter flow heat exchanger has been analyzed with steel, aluminum and copper as inner pipe materials with water and ammonia as cold fluids. This work has been done with different roughnesses of pipes but same mass flow rates for hot and cold fluids, i.e., 0.08 kg/s.

Roughness which is extremely important for mechanical point of view is the component of surface texture and can be determined through deviations in normal vector's direction where large deviation indicates rough, whereas small deviation indicates smooth surfaces. High value of roughness is objectionable due to complexity in manufacturing, and manufacturing cost increases by decreasing the surface roughness. Surface roughness can be measured by surface roughness comparator manually, but generally it is measured by profilometer. Roughness is denoted by ϵ_r . There are two types of roughnesses: one is absolute roughness, and other is relative roughness. Absolute roughness is the measure of surface roughness of a material and this roughness is important for calculating pressure drop particularly in turbulent flow regime, but relative roughness is the ratio of roughness to diameter of pipe and it is used to measure the roughness of inner surface of the pipe. The value of friction factor can be found from moody chart by relative roughness [6]. If ϵ_r is roughness of pipe (mm) and D is the diameter of pipe (mm), then relative roughness can be expressed as:

$$\text{Relative roughness} = \epsilon_r / D \quad (1)$$

Chen et al. have done work on entropy generation concepts on various thermodynamic systems; irreversible engine, pin fin heat sinks and also isothermal crystallization processes. After analyses, they suggested minimum

entropy generation principle for better performance/operation of thermodynamic systems [7–11]. Exergy analyses at different conditions have been performed on heat exchangers and power plants by Geete et al. and Ibrahim et al., and after analyses they found minimum exergy destruction is good for better outputs from thermal systems [12–16]. Chen et al., Feng et al., Guo et al. and other researchers have worked on entransy concepts for heat exchanging devices, and they applied entransy dissipation, entransy dissipation-based thermal resistance and entransy dissipation number on thermodynamic systems for comparative performance analyses and concluded that these parameters should be minimum [17–28]. In this research work, rates of entropy generation, exergy destruction, entransy dissipation, entransy dissipation-based thermal resistance, entransy dissipation numbers, effectiveness and entropy generation numbers have been calculated at different operating conditions to get better conditions at which performance of counter flow double-pipe heat exchanger will be the best.

2 Methodology

Outlet temperatures for double-pipe counter flow heat exchanger have been investigated with water and ammonia as cold fluids and steel, aluminum and copper as inner pipe materials at the different roughnesses of the inner surfaces of the inner pipes by CFD tools. In this research work, commercial code has been used for analyses in ANSYS Fluent 15.0 software. K- ϵ modeling has been used for performance analyses and taken from the literature. It is well established fact that K- ϵ model has been used in RANS. For validation, rates of entropy generation, exergy destruction and entransy dissipation have been found with entransy dissipation-based thermal resistances, entropy generation numbers and entransy dissipation numbers for the same conditions, and the following methodology has been adopted for this research work. The first law of thermodynamics for cyclic process states that the cyclic integration of heat is equal to the cyclic integration of work, but when the first law is applied for a process, then a thermodynamic property comes out which is internal energy. Similarly, the second law of thermodynamics for cyclic process gives information about systems: heat engine, heat pump and refrigerator, but when this law is applied for a process, then a new property appears which is entropy (S). It has been found that for a closed system, change in entropy for irreversible process is more than the integration of dQ/T for that process; it means some entropy is generated which indicates losses in the process. Internal irreversibility or dissipative work is the main cause for entropy generation, and it is always positive or zero (for

reversible process). Irreversibility or losses can be calculated by entropy generation for heat exchangers, and it is calculated as [7–11]:

$$TdS_{\text{gen}} = m_h C_{ph} \int (T_h) + m_c C_{pc} \int (T_c) \quad (2)$$

$$TdS_{\text{gen}} = m_h C_{ph} \int_{T_{hi}}^{T_{ho}} T_h + m_c C_{pc} \int_{T_{ci}}^{T_{co}} T_c \quad (3)$$

$$dS_{\text{gen}} = m_h C_{ph} \ln (T_{ho}/T_{hi}) + m_c C_{pc} \ln (T_{co}/T_{ci}) \quad (4)$$

where dS_{gen} is the rate of entropy generation in kW/K. The exergy or available energy of a system can be defined as maximum possible work which is extracted from that system when system approaches the thermodynamic equilibrium state with its surrounding called dead state (i.e., P_a and T_a). Exergy is that kind of property which depends on state of system and surrounding, and when system reaches dead state, exergy of system becomes zero. Reversible work transfer from the system is always greater than actual work transfer, and the difference between these works is known as irreversibility of the system; the term $T_a S_{\text{gen}}$ is the decrease in exergy of the system because of irreversibility. This concept was given by Gouy-Stodola, and he said the rate of exergy losses or exergy destruction rate in a process is proportional to the rate of entropy generation and ambient temperature. Exergy destruction rates for double-pipe counter flow heat exchanger have been calculated at various conditions by the following equation [12–16]:

$$0 = [m_h C_{ph} \{ (T_{hi} - T_{ho}) - T_a \ln (T_{hi} - T_{ho}) \}] - [m_c C_{pc} \{ (T_{co} - T_{ci}) - T_a \ln (T_{co} - T_{ci}) \}] - \varphi_{\text{des}} \quad (5)$$

$$\begin{aligned} \text{Exergy destruction rate } (\varphi_{\text{des}}) \\ = [m_h C_{ph} \{ (T_{hi} - T_{ho}) - T_a \ln (T_{hi} - T_{ho}) \}] \\ - [m_c C_{pc} \{ (T_{co} - T_{ci}) - T_a \ln (T_{co} - T_{ci}) \}] \end{aligned} \quad (6)$$

where m_h and m_c are flow rates (kg/s), C_{ph} and C_{pc} are specific heats (kJ/kg-K) of hot and cold fluids, respectively, T_{hi} and T_{ci} are inlet temperatures (Kelvin), T_{ho} and T_{co} are outlet temperatures (Kelvin) of hot and cold fluids, T_a is ambient temperature and φ_{des} is exergy destruction rate (kW) [12–16]. The performance of heat exchanger can be analyzed by entransy which is the ability of heat transfer through heat exchanger, and it can be clarified by analogy between electrical and thermal parameters. If electrical and thermal potentials are V and T , and electrical and heat fluxes are I and Q , respectively, then electrical resistance will be (V/I) and thermal resistance will be (T/Q) . Electricity and heat transfer rates are I and Q , Ohm's law is $I = K_e A$

(dV/dn) , Fourier's law is $Q = K A (dT/dn)$, electrical charge stored is Q , and heat stored is $Q(U) = m C_v T$. Electric capacitance is Q/V , and thermal capacitance is U/T . Similarly, electrical potential energy stored in a capacitor is $QV/2$, and thermal potential energy stored in a system is $UT/2$. Thus, entransy (G) is defined as the half of the product of internal energy (U) and temperature (T) and expressed as [17–27];

$$G = 1/2 UT \quad (7)$$

Rate of entransy dissipation which is losses can be calculated by mass flow rates, specific heats and inlet/outlet temperatures of the hot and cold fluids, and it can be expressed as:

$$G_d = 1/2 [m_h C_{ph} \{ (T_{hi})^2 - (T_{ho})^2 \}] - 1/2 [m_c C_{pc} \{ (T_{co})^2 - (T_{ci})^2 \}] \quad (8)$$

where G is entransy (kW-K), G_d is rate of entransy dissipation (kW-K) and U is internal energy (kW). For performance analysis, entransy dissipation-based thermal resistance for heat exchanger is also found which is related to rate of entransy dissipation and heat transfer through heat exchanger and can be expressed as:

$$R_t = G_d / Q^2 \quad (9)$$

where R_t is entransy dissipation-based thermal resistance (K/kW) and Q is rate of heat transfer through heat exchanger (kW). A dimensionless number called entransy dissipation number is introduced by researchers for performance analysis of heat exchanger, and this term can be found by rate of entransy dissipation, heat transfer through heat exchanger and maximum temperature difference in heat exchanger (i.e., T_{hi} and T_{ci}). Entransy dissipation number (EDN) can be expressed as [28]:

$$EDN = G_d / [Q (T_{hi} - T_{ci})] \quad (10)$$

This EDN equation can be modified with effectiveness (ε) which is the ratio of actual heat transfer (Q) to maximum heat transfer (Q_{max}) through heat exchanger and can be written as [1–4];

$$\varepsilon = (Q) / (Q_{\text{max}}) \quad (11)$$

$$\varepsilon = [(m_h C_{ph})_{\text{max}} (T_{hi} - T_{ho})] / [(m_f C_{pf})_{\text{min}} (T_{hi} - T_{ci})]_{\text{max}} \quad (12)$$

$$\text{or } \varepsilon = [(m_c C_{pc})_{\text{max}} (T_{co} - T_{ci})] / [(m_f C_{pf})_{\text{min}} (T_{hi} - T_{ci})]_{\text{max}} \quad (13)$$

So, EDN can be modified as;

$$EDN = G_d / [\varepsilon Q_{\text{max}} (T_{hi} - T_{ci})] \quad (14)$$

$$EDN = G_d / [\varepsilon \{ (m_f C_{pf})_{\text{min}} (T_{hi} - T_{ci}) \} (T_{hi} - T_{ci})] \quad (15)$$

$$\text{or } EDN = G_d / [\varepsilon (m_f C_{pf})_{\text{min}} (T_{hi} - T_{ci})^2] \quad (16)$$

In this research work, entropy generation number has been calculated for the heat exchanger and it should

be as minimum as possible for the better performance of the heat exchanger. It is the ratio of entropy generation during irreversible heat transfer through the heat exchanger to the minimum heat capacity of the flowing fluid [29].

$$N_{eg} = dS_{gen}/(mC_p)_{min} \quad (17)$$

In the present work, CFD analyses of double-pipe heat exchanger for counter flow have been performed where water is used as hot fluid while water or ammonia is used as cold fluids (which flow through heat exchanger) with steel, aluminum and copper as inner pipe materials with different roughnesses of pipes. After simulation, numerical validation has been done and compared all results and proved which pipe material (with surface roughness) and cold fluid give best effectiveness or rate of heat transfer but lowest rates of entropy generation, exergy and entransy dissipation and entransy dissipation number. Geometry of double-pipe heat exchanger is shown in Fig. 2, and four different meshes are given in Table 2 [5]. A method has been done to decide mesh for CFD analysis. For example, outlet temperatures of cold and hot fluids for mesh 3 and mesh 4 do not vary significantly (as in Table 2), so mesh 3 has been chosen for research work which has 485,831 elements and 507,656 nodes.

Fig. 2 Geometry of double-pipe counter flow heat exchanger

3 Results

Temperature counters have been found by CFD analyses at different operating conditions as shown in Figs. 3 and 4, and the conditions are: (a) inlet temperature of hot fluid (water) is 350 K, inlet temperature of cold fluid (water) is 300 K, mass flow rates of hot and cold fluids are 0.08 kg/s, specific heat of water is 4.186 kJ/kg-K, inner pipe materials are steel, aluminum and copper, and outer pipe material is steel; and (b) inlet temperature of cold fluid (ammonia) is 210 K, inlet temperature of hot fluid (water) is 300 K, and specific heat of ammonia is 4.744 kJ/kg-K. Results which have been obtained from CFD analyses for all three materials for all three cases of different cold fluids and roughnesses of inner pipes are mentioned in Tables 3, 4 and 5. Outlet temperatures and rates of heat transfer for each condition have been tabulated.

Results from analyses show that maximum heat transfer between hot and cold fluids can be achieved if thermal conductivity of the inner pipe of double-pipe heat exchanger is higher. Rate of heat transfer and effectiveness increases with the thermal conductivity of the material, and these parameters also change with the change in cold fluid and roughness of the pipe. Rates of entropy generation, exergy destruction and entransy dissipation with entransy dissipation-based thermal resistances, entransy dissipation numbers and entropy generation numbers are shown in Tables 6 and 7.

Comparative curves have also been plotted for different inner pipe materials and different roughnesses of pipes between the rates of heat transfer through heat exchanger, entropy generation, exergy destruction, entransy dissipation, entransy dissipation-based thermal resistances, entransy dissipation numbers and entropy generation numbers as shown in Figs. 5, 6, 7, 8, 9, 10 and 11. These curves indicate: (1) maximum percentage decrements in the rate of heat transfer between flowing fluids (i.e., 48.075, 31.372 and 28.705%) were found for Cu–water, steel–ammonia and Al–water combinations as inner pipe materials and cold fluids when surface roughnesses were highest but maximum percentage increment (i.e., 114.162%) achieved with Cu–water combination when

Table 2 Outlet temperatures of four meshes

Mesher	Iteration converged	Inlet temperature of cold fluid (K)	Inlet temperature of hot fluid (K)	Outlet temperature of cold fluid (K)	Outlet temperature of hot fluid (K)
1	191	300.0	350.0	308.450	342.027
2	140	300.0	350.0	308.333	342.135
3	205	300.0	350.0	308.216	342.242

Fig. 3 Temperature contours for steel, aluminum and copper at conditions (a)

Fig. 4 Temperature contours for steel, aluminum and copper at conditions (b)

Table 3 Results with steel pipe and change in pipe's roughness with different cold fluids

Inner pipe material	Cold fluid	Roughness	Inlet temperature (K)		Outlet temperature (K)		Rate of heat transfer (kW)
			Cold fluid	Hot fluid	Cold fluid	Hot fluid	
Steel	Water	0.0	300	350	308.450	342.027	2.669
		0.2	300	350	308.333	342.135	2.633
		0.4	300	350	308.216	342.242	2.597
	Ammonia	0.0	210	300	232.288	275.458	9.314
		0.2	210	300	228.922	279.380	7.825
		0.4	210	300	225.663	283.156	6.392

Table 4 Results with aluminum pipe and change in pipe's roughness with different cold fluids

Inner pipe material	Cold fluid	Roughness	Inlet temperature (K)		Outlet temperature (K)		Rate of heat transfer (kW)
			Cold fluid	Hot fluid	Cold fluid	Hot fluid	
Al	Water	0.0	300	350	312.940	337.566	4.163
		0.02	300	350	310.812	339.629	3.473
		0.04	300	350	308.964	341.136	2.968
	Ammonia	0.0	210	300	232.813	274.991	9.491
		0.02	210	300	230.656	277.403	8.576
		0.04	210	300	229.455	278.050	8.330

Table 5 Results with copper pipe and change in pipe's roughness with different cold fluids

Inner pipe material	Cold fluid	Roughness	Inlet temperature (K)		Outlet temperature (K)		Rate of heat transfer (kW)
			Cold fluid	Hot fluid	Cold fluid	Hot fluid	
Cu	Water	0.0	300	350	317.610	332.929	5.716
		0.015	300	350	311.402	338.809	3.747
		0.03	300	350	308.889	340.136	3.266
	Ammonia	0.0	210	300	235.841	266.021	12.895
		0.015	210	300	233.619	270.014	11.380
		0.03	210	300	232.035	272.768	10.335

Table 6 Entropy, exergy and entransy analyses for water as hot and cold fluids

Inner pipe material	Pipe roughness	dS_{gen} (kW/K)	Ψ_{des} (kW)	G_d (kW-K)	R_d (K/kW)	EDN	ε	N_{eg}
Steel	0.0	0.00158	5.690	62.858	8.819	0.470	0.160	4.737
	0.2	0.00156	5.658	62.618	9.027	0.475	0.157	4.672
	0.4	0.00154	5.624	62.370	9.242	0.480	0.155	4.607
Al	0.0	0.00202	3.846	103.321	5.959	0.496	0.248	6.060
	0.02	0.00178	4.037	91.747	7.606	0.528	0.207	5.326
	0.04	0.00126	1.099	111.703	12.678	0.752	0.177	3.791
Cu	0.0	0.00235	2.948	130.853	4.004	0.457	0.341	7.041
	0.015	0.00161	1.809	123.408	8.786	0.658	0.223	4.806
	0.03	0.00118	0.280	119.492	13.556	0.804	0.177	3.549

surface was smooth. (2) Maximum percentage changes for entropy generation, exergy destruction, entransy dissipation, entransy dissipation-based thermal resistance,

entransy dissipation number, effectiveness and entropy generation number were found (2.531, 1.159, 0.776, 4.796, 2.127, 3.125 and 2.744%, respectively) for steel–water,

Table 7 Entropy, exergy and entransy analyses for water as hot and ammonia as cold fluids

Inner pipe material	Pipe roughness	dS_{gen} (kW/K)	Ψ_{des} (kW)	G_d (kW-K)	R_d (K/kW)	EDN	ε	N_{eg}
Steel	0.0	0.00970	31.654	494.056	7.314	0.667	0.272	2.897
	0.2	0.00889	30.473	424.252	8.897	0.682	0.230	2.657
	0.4	0.00795	29.248	349.687	10.991	0.688	0.187	2.374
Al	0.0	0.00999	32.371	490.717	6.996	0.651	0.277	2.983
	0.02	0.00938	31.260	457.361	7.987	0.671	0.251	2.801
	0.04	0.00818	27.597	502.084	9.292	0.758	0.243	2.443
Cu	0.0	0.00378	17.619	1034.50	7.986	1.009	0.377	1.131
	0.015	0.00518	19.447	873.617	8.664	0.966	0.333	1.548
	0.03	0.00600	20.904	763.242	9.177	0.929	0.302	1.792

Fig. 5 Percentage decrement in heat transfer with steel pipe at different roughnesses

(18.041, 7.6, 29.221, 50.273, 3.148, 31.25 and 18.053%, respectively) for steel–ammonia, (37.623, 71.424, 8.112, 112.753, 51.612, 28.629 and 37.442%, respectively) for Al–water, (18.118, 14.747, 2.316, 32.818, 16.436, 12.274 and 18.102%, respectively) for Al–ammonia, (49.787, 90.502, 8.682, 238.561, 75.93, 48.093 and 49.595%, respectively) for Cu–water and (58.73, 18.644, 26.221, 14.913, 7.928, 19.893 and 58.443%, respectively) for Cu–ammonia combinations at highest surface roughness, but comparatively less percentage changes for these parameters were found (1.265, 0.562, 0.381, 2.358, 1.063, 1.875 and 1.372%, respectively) for steel–water, (8.35, 3.73, 14.128, 21.643, 2.248, 15.441 and 8.284%, respectively) for steel–ammonia, (11.881, 4.966, 11.201, 27.638, 6.451, 16.532 and 12.112%,

Fig. 6 Percentage decrement in heat transfer with aluminum pipe at different roughnesses

Fig. 7 Percentage decrement in heat transfer with copper pipe at different roughnesses

Fig. 8 Percentage increment in heat transfer with different inner pipe materials

respectively) for Al–water, (6.106, 3.432, 6.797, 14.165, 3.072, 9.386 and 6.101%, respectively) for Al–ammonia, (31.489, 38.636, 5.689, 119.43, 43.982, 34.604 and 31.742%, respectively) for Cu–water and (37.037, 10.375, 15.551, 8.489, 4.261, 11.671 and 36.87%, respectively) for Cu–ammonia combinations for smoother surfaces of inner pipes of double-pipe counter flow heat exchanger.

Computer software has also been developed in this research work called effect of surface roughness on the

performance of heat exchanger (ESRPHEx) as shown in Fig. 12, and this computer software is useful to eliminate human errors during mathematical calculations and also helpful to reduce time consumption during the analyses [30].

4 Conclusion

In this research work, comparative analyses of heat exchanger with steel, aluminum and copper as inner pipe materials and with water and ammonia as cold fluids have been done and observed that the maximum amount of heat transfer between flowing fluids and effectiveness of heat exchanger is 12.895 kW and 0.377, which have been found when copper was used as inner pipe with smooth surface finish and ammonia as cold fluid. It has also been concluded that the following conditions are required for best performance from a heat exchanger: entropy generation rate, entropy generation number, exergy destruction rate, entransy dissipation rate, entransy dissipation-based thermal resistance and entransy dissipation number should be minimum. So, minimum rate of entropy generation is 0.00118 kW/K, entropy generation number is 1.131, exergy destruction rate is 0.280 kW, entransy dissipation-based thermal resistance is 4.004 K/kW, and entransy dissipation number is 0.457 which have been found with copper pipe. Maximum percentage increment has been found when copper was used as inner pipe material with smooth surface. It has also been observed that when water was used as cold fluid, the percentage changes in entropy generation, exergy destruction, entransy dissipation, entransy dissipation-based thermal resistance, entransy dissipation number, effectiveness and entropy generation number increase with thermal conductivity of inner pipe, and percentage changes in these parameters were less with ammonia as compared to water at same operating conditions. After analyses, high heat capacity of fluid (i.e., ammonia as cold fluid) and high conductive material (copper as inner pipe) with smooth surface have been recommended to get best performance from heat exchanger.

Fig. 9 a, b Percentage change in properties with steel pipe at different roughnesses: **a** water and **b** ammonia as cold fluids

Fig. 10 a, b Percentage change in properties with aluminum pipe at different roughnesses: **a** water and **b** ammonia as cold fluids

Fig. 11 a, b Percentage change in properties with copper pipe at different roughnesses: **a** water and **b** ammonia as cold fluids

Fig. 12 Developed computer software for performance analyses

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Cengel AY (2003) Heat transfer: a practical approach. Tata McGraw-Hill Publication, New York
- Holman JP (2009) Heat transfer. Tata McGraw-Hill Publications, New York
- Lienhard HJ (2008) A heat transfer text book. Phlogiston Press Cambridge, Massachusetts
- Whitaker S (1983) Fundamental principles of heat transfer. Robert E. Krieger Publishing Company, Inc. Krieger Drivemalabar, Florida
- Pathak R, Geete A (2019) Thermal performance analyses of concentric pipe counter flow heat exchanger at different operating conditions by CFD. *i-Manager's J Mech Eng*
- Farshad FF, Rieke RR (2006) Surface-roughness design values for modern pipes. *SPE Drilling & Completion*
- Chen LG, Ma K, Ge YL, Sun FR (2017) Minimum entropy generation path for an irreversible light-driven engine with reacting system and linear phenomenological heat transfer law. *Environ Eng Manag J* 16(9):2035–2043
- Chen LG, Wu C, Sun FR (1999) Finite time thermodynamic optimization or entropy generation minimization of energy systems. *J Nonequilibrium Thermodyn* 24(4):327–359
- Chen LG, Xia SJ, Sun FR (2018) Entropy generation minimization for isothermal crystallization processes with a generalized mass diffusion law. *Int J Heat Mass Transf* 116:1–8
- Chen LG, Yang AB, Xie ZH, Feng HJ, Sun FR (2017) Constructal entropy generation rate minimization for cylindrical pin-fin heat sinks. *Int J Therm Sci* 111:168–174
- Chen LG, Zhang L, Xia SJ, Sun FR (2018) Entropy generation minimization for hydrogenation of CO₂ to light olefins. *Energy* 147:187–196
- Geete A (2017) Exergy, entransy and entransy based thermal resistance analyses of double pipe heat exchanger with different pipe materials. *Heat Transf Res* 48(18):1625–1636. <https://doi.org/10.1615/HeatTransRes.2017015641>
- Geete A (2015) Exergy, exergy destruction rate and exergy efficiency analysis of thermal power plants by computer software at various operating conditions. *i-Manager's J Future Eng Technol* 11(1):7–22
- Geete A, Khandawala AI (2014) Exergy analysis for 120 MW thermal power plant with different inlet temperature conditions. *Int J Res Eng Technol* 2(1):21–30
- Geete A, Khandawala AI (2014) Exergy analysis for 120 MW thermal power plant with different inlet pressure conditions and generate exergy outlet curves for different components. *Asian Acad Res J Multidiscip* 1(18):234–247
- Ibrahim TI, Mohammed MK, Awad OI, Abdalla AN, Basrawi F, Mohammed MN, Najafi G, Mamat R (2018) A comprehensive

- review on the exergy analysis of combined cycle power plants. *Renew Sustain Energy Rev* 90:835–850
17. Chen LG (2012) Progress in entransy theory and its applications. *Chin Sci Bull* 57(34):4404–4426
 18. Chen LG (2014) Progress in optimization of mass transfer processes based on mass entransy dissipation extremum principle. *Sci China Technol Sci* 57(12):2305–2327
 19. Chen LG, Xiao QH, Feng HJ (2018) Constructal optimizations for heat and mass transfers based on the entransy dissipation extremum principle, performed at the Naval University of Engineering; a review. *Entropy* 20(1):74
 20. Cheng XT, Liang XG (2013) Entransy, entransy dissipation and entransy loss for analyses of heat transfer and heat-work conversion processes. *J Therm Sci Technol* 8(2):337–352
 21. Feng HJ, Chen LG, Liu X, Xie ZH, Sun FR (2016) Generalized constructal optimization of strip laminar cooling process based on entransy theory. *Sci China Technol Sci* 59(11):1687–1695
 22. Feng HJ, Chen LG, Xie ZH, Sun FR (2016) Constructal entransy dissipation rate minimization of a rectangular body with nonuniform heat generation. *Sci China Technol Sci* 59(9):1352–1359
 23. Feng HJ, Chen LG, Xie ZH (2018) Constructal optimizations for “+” shaped high conductivity channels based on entransy dissipation rate minimization. *Int J Heat Mass Transf* 119:640–646
 24. Guo ZY, Zhu HY, Liang XG (2007) Entransy—a physical quantity describing heat transfer ability. *Int J Heat Mass Transf* 50:2545–2556
 25. Wang C, Zhu Y (2018) Entransy analysis on boiler air pre-heater with multi-stage LHS unit. *Appl Therm Eng* 130:1139–1146
 26. Xia SJ, Chen LG, Sun FR (2016) Optimization of equimolar reverse constant- temperature mass-diffusion process for minimum entransy dissipation. *Sci China Technol Sci* 59(12):1867–1873
 27. Xia SJ, Chen LG, Xie ZH, Sun FR (2016) Entransy dissipation minimization for generalized heat exchange process. *Sci China Technol Sci* 59(10):1507–1516
 28. Guo JF, Cheng L, Xu MT (2009) Entransy dissipation number and its application to heat exchanger performance evaluation. *Chin Sci Bull* 54(15):2708–2713
 29. Bejan A (1982) *Entropy generation through heat and fluid flow*. Wiley, New York
 30. Holzner S (2009) *Visual Basic 6.0 programming black book*. Dreamtech Press Publication, New Delhi

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