EFFECTS OF GEOMETRIC PARAMETERS ON ENTROPY GENERATION IN FIRE-TUBE STEAM BOILER'S HEAT EXCHANGER

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Abstract: This paper presents a parametric study on fire-tube steam boilers' heat exchanging unit using Entropy Generation Minimization (EGM) technique. Mathematical equation that models entropy generation rate ($\dot{S}_{gen}$), and entropy generation number (N_s), were formulated. The entropy generation number was related to the geometric features of the system. Solving the equations showed the effects of each geometric feature on both pressure drop and N_s. Correlation equation relating dimensionless fire-tube length to dimensionless tube diameter was also obtained. The obtained correlation equation is a tool to be incorporated into fire-tube steam boiler design, so as to account for entropy generation during design.

Keyword: entropy generation minimization, heat exchanging unit, geometric features

1. INTRODUCTION

Entropy is a measure of the extent of disorderliness/randomness in a thermodynamic system. It can be used to distinguish between reversible and irreversible processes [1]. Its analysis can be used to assess the level of energy quality in a system. Entropy generation rate investigates irreversibility by the second law of thermodynamics [2, 3]. Determination of entropy generation is also important to enhance system performance because entropy generation measures destruction of available work in the system [4].

Entropy Generation Minimization (EGM) is a method of optimization of the thermodynamic imperfections and fluid flow irreversibility [5]. It involves the use of the deterministic or heuristic approach to investigate the area with the highest rate of entropy generation in a system, as well as the cause(s) of such entropy generation. It also uses either of these approaches to minimize entropy in a system, thereby increasing the useful work or energy of the system [6]. Recent application of EGM includes its use in parametric studies.

Parametric study of entropy minimization on the heat exchanging unit of steam boilers has become very important, in view of high premium placed on the use of steam boilers for various industrial processes. Steam boilers are those closed vessels which are used in the production of steam from water by combustion of fuel [7]. The steam produced finds applications in many other production processes. Thus, it is very important to

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effectively assess the energy resources utilization and outputs in steam boilers to ensure adequate energy management [8]. Steam boilers have various components, but the component which is responsible for the phase change of water is the heat exchanging unit [9]. It is placed directly after the combustion unit, and it exemplifies a cross flow heat exchanger type. It takes in the hot flue gas coming out of the combustion unit, and the heat carried by this gas is used to transform liquid water to steam in the unit [10]. According to Bejan [11], exergy analysis and the minimization of exergy destruction can be used by themselves especially in areas where the total cost of the installation is dominated by the cost due to thermodynamic irreversibility. Steam boilers heat exchanger can be conceptualized on the basis of entropy generation minimization, considering its objectives and physical constraint.

Although many complex analyses of EGM on heat exchangers have been reported before now, the vast majority of them focused on actual optimization of the studied systems based on thermodynamic properties, while just very few of such analyses studied parametric effects of system geometry on EGM. This work aims to investigate the effects of fire-tube geometric parameters on entropy generation in the fire-tube steam boilers' heat exchanging unit. Investigating the effects of 'size' on the performance of steam boiler's heat exchanger as it is done in this study is theoretically similar to what obtains in constructive designs, where flow configurations are generated in energy conversion systems for optimum performance of such systems [12-15]. Mathematical equation that models entropy generation rate in the steam boiler will be formulated from fundamental entropy equation. This model will be derived from schematic illustration of steam boiler heat exchanging unit. Available thermodynamic properties for a fire-tube steam boiler [16] will be used for the parametric analysis.

2. MATHEMATICAL REPRESENTATION OF SYSTEM'S ENTROPY GENERATION RATE

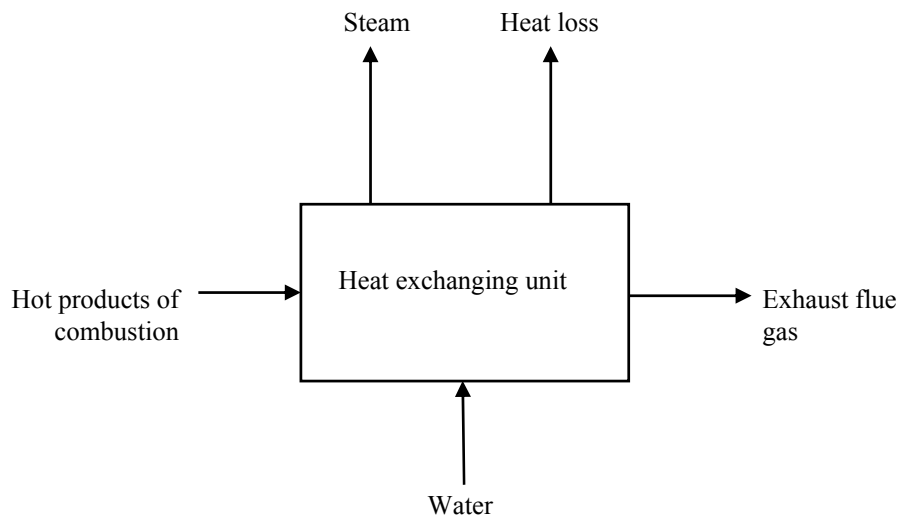The schematic of the control volume of the system is shown in Figure 1.

Fig. 1. Schematic diagram of heat exchanging units in steam boilers [7].

Considering Figure 1, there are two streams flowing through the heat exchanging unit, hot products of combustion, and water. Entropy generation rate in the heat exchanging unit is due to the two streams and heat loss, and it is expressed as

$$\dot{S}_{gen} = \dot{m}_p \left(c_{pp} \ln \frac{T_g}{T_p} - R_p \ln \frac{P_g}{P_p} \right) + \dot{m}_w \left(c_{pw} \ln \frac{T_s}{T_w} - R_w \ln \frac{P_s}{P_w} \right) + \frac{Q_l}{T_a} \qquad (1)$$

where:

$$Q_l = \text{heat loss} = \dot{m}_p c_{pp} (T_g - T_p) + \dot{m}_w c_{pw} (T_s - T_w) \qquad (2)$$

The first term on the right hand side of equation (1) is the entropy generation rate due to the hot product stream, while the second term is the entropy generation rate due to the water stream. The third term is the entropy generation rate due to heat loss in the system.

2.1 Non-dimensionalization of Entropy Generation Rate
Capacity flow rate on the water side is expressed as:

$$C_{max} = \dot{m}_w c_{pw} \tag{3}$$

and that on the hot product side is:

$$C_{min} = \dot{m}_p c_{pp} \tag{4}$$

Following Vargas and Bejan; Alebrahim and Bejan [17, 18], the entropy generation number (N_s) is obtained by dividing the entropy generation rate by the minimum capacity flow rate. Thus, N_s was obtained by using C_{min} in Equation (4) to scale $\dot{S}_{gen}$ in equation (1). Also, the ambient properties were used to scale all temperatures and pressures in the expressions. That is:

$$\dot{T}_g = \frac{T_g}{T_a}; \dot{P}_g = \frac{P_g}{P_a} \tag{5}$$

The N_s equation was obtained as:

$$N_s = \frac{\dot{S}_{gen}}{\dot{m}_p c_{pp}} = \frac{1}{\dot{m}_p c_{pp}} \left[\dot{m}_p \left(c_{pp} \ln \frac{T_g}{T_p} - R_p \ln \frac{P_g}{P_p} \right) + \dot{m}_w \left(c_{pw} \ln \frac{T_s}{T_w} - R_w \ln \frac{P_s}{P_w} \right) + \frac{(\dot{m}_p c_{pp}(T_p - T_g) + \dot{m}_w c_{pw}(T_w - T_s))}{T_a} \right] \tag{6}$$

Simplifying equation (6) gives:

$$N_s = \left(\ln \frac{\dot{T}_g}{\dot{T}_p} - k_p \ln \frac{\dot{P}_g}{\dot{P}_p} \right) + y \left(\ln \frac{\dot{T}_s}{\dot{T}_w} - k_w \ln \frac{\dot{P}_s}{\dot{P}_w} \right) + (\dot{T}_g - \dot{T}_p) + y (\dot{T}_s - \dot{T}_w) \tag{7}$$

And by collecting the terms involving y together, equation (7) becomes:

$$N_s = \left(\ln \frac{\dot{T}_g}{\dot{T}_p} - k_p \ln \frac{\dot{P}_g}{\dot{P}_p} \right) + (\dot{T}_g - \dot{T}_p) + y \left(\left(\ln \frac{\dot{T}_s}{\dot{T}_w} - k_w \ln \frac{\dot{P}_s}{\dot{P}_w} \right) + (\dot{T}_s - \dot{T}_w) \right) \tag{8}$$

where:

$$y = \frac{\dot{m}_w c_{pw}}{\dot{m}_p c_{pp}}; k_p = \frac{R_p}{c_{pp}} \text{ and } k_w = \frac{R_w}{c_{pp}} \tag{9}$$

3. GEOMETRY OF THE BOILER HEAT EXCHANGING UNIT

For a fire-tube steam boiler which is the focus of this work, the heat exchanging unit typifies a cross-flow, shell and tube heat exchanger. Hot flue gas flows through the tubes in a number of passes before going out into the atmosphere through the exhaust pipe. Water flows through the boiler shells around the tubes. As such, there are four major dimensions that describe the geometry of the fire-tube boiler heat exchanging unit under consideration. They are the diameter of fire tube, d_t; length of fire tube, L_t; diameter of boiler shell, d_s and length of boiler shell, L_s. It is assumed that d_s and L_s are fixed by the boiler surface type. Thus, d_t and L_t remain the geometric parameters that play trade-off roles which lead to the minimization of N_s. The geometry is subject to its volume constraint;

$$V = \frac{\pi}{4} d_t{}^2 L_t \tag{10}$$

Thus, the entire entropy minimization procedure is placed on a fixed volume basis by using $V^{1/3}$ as length scale in the non-dimensionless formulation of all the lengths:

$$(ɗ_t, Ĺ_t, ɗ_s, Ĺ_s) = \frac{(ɗ_t, Ĺ_t, ɗ_s, Ĺ_s)}{V^{1/3}} \tag{11}$$

According to Patel and Mavani [19], the pressure drop in the tube is given by the expression:

$$P_p - P_g = (4f\frac{LNp}{d})\frac{G^2}{2\rho}; \tag{12}$$

$G = \frac{\dot{m}_p}{A_t}$ = mass velocity of the hot product, $A_t = \frac{N_t \pi d_t^2}{4N_p}$ = total area of the tubes. Using the atmospheric pressure (P_a) and $V^{1/3}$ to scale pressure and length parameters respectively in equation (12), and substituting for G and A_t, the pressure drop equation assumes the following dimensionless form:

$$\dot{P}_p - \dot{P}_g = \frac{32\dot{m}_p^2 N_p^3}{\pi^2 P_a d_t^4 \rho V^{4/3} N_t^2}(f\frac{Ĺ_t}{ɗ_t}) \tag{13}$$

Combining Equations (8) and (13) shows that $N_s = f(Ĺ_t, ɗ_t)$.

4. COMPUTATIONAL SOLUTION OF THE ENTROPY GENERATION NUMBER (N_S) AND PRESSURE DROP EQUATIONS

In order to determine the extent of entropy generation due to heat transfer and fluid flow in the system, computer codes were developed in FORTRAN 95 to solve equations (8) and (13). Operational data of a fire tube steam boiler that uses diesel as its fuel were used to illustrate the minimization technique being investigated in this study. Ohijeagbon et al., 2013[b] [20] have obtained numerical values for the thermodynamic properties of material streams for this particular steam boiler.

Steam pressure P_s and water pressure P_w at their respective temperatures were obtained from Rogers and Mayhew [21]. Taking ambient temperature and pressure as T_a = 298 K and P_a = 1.01325 bar, dimensionless temperature and pressure values were computed for the streams using equation (5). The properties R_w = 0.3473 kJ/kgK and C_{pw}= 4.2385 kJ/kgK for water at 353 K were obtained directly from the thermodynamic properties table. However, values for these properties for hot products of combustion of diesel were not obtainable directly from the table. Guha [22] gave the following equations for obtaining each of these properties:

$$\frac{C_{p,combust}}{C_{p,air}} = \frac{1+r_{fa}(\Re\mathcal{J}_0 + \mathcal{J}_1 T - \frac{\mathcal{J}_2}{T^2})}{1+r_{fa}} \tag{14}$$

and

$$\frac{R_{combust}}{R_{air}} = \frac{1+\Re r_{fa}}{1+r_{fa}}. \tag{15}$$

Also specified were $\Re$ = 0.969, $\mathcal{J}_0$ = 2.420, $\mathcal{J}_1$= 0.0002982, and $\mathcal{J}_2$= 77800 for diesel. In equations (14) and (15), r_{fa} = actual air fuel ratio, $\Re, \mathcal{J}_0, \mathcal{J}_1$, and $\mathcal{J}_2$ are constants based on fuel type, $C_{p,combust}$= specific heat at constant pressure for combustion product and $R_{combust}$ = gas rate constant for combustion product. According to [7], r_{fa} may be taken as 17 for diesel operated boilers.

The constants y, k_p and k_w were determined using Equation (9).

The unknown terms on the right hand side of dimensionless pressure drop equation (13) were determined from the fire-tube geometry. The maximum allowable fire-tube volume V was determined from equation (10). The friction factor (f) is a constant, and it was determined from Fanning friction factor chart for flow through cylindrical conduit, which presents values for friction factor as a function of Reynolds number (Re) and relative roughness of pipe [23].

5. RESULTS AND DISCUSSION

The entropy minimization procedure involved translating the entropy generation number equation (8) and dimensionless pressure drop equation (13) into computer codes using FORTRAN 95. The codes were written in such a way that each of the fire-tube dimensionless diameter and length values were varied in turn, with the other kept constant, taking into consideration the maximum allowable volume constraint. In the first instance, $đ_t$ was varied between 0.25 and 0.50 at interval 0.01, while keeping L_t constant at 2.5. Thus, N_s values that correspond to each $đ_t$ value were obtained.

5.1. Effects of fire-tube diameter on pressure drop

Figure 2 shows the relationship between the diameter of the fire-tube and pressure drop. As it would be expected, the pressure drop in fire-tube decreases as the fire-tube diameter increases. During the design of heat exchangers, a maximum allowable value of pressure drop is usually specified. This is because it is often required to keep pressure drop in heat exchanging units as minimum as possible, so as to minimize cost due to pumping. According to [6], the primary aim of such designs is to obtain a high heat transfer rate without exceeding the allowable pressure drop. Also, pressure drop has a significant effect on the level of irreversibility in a system.
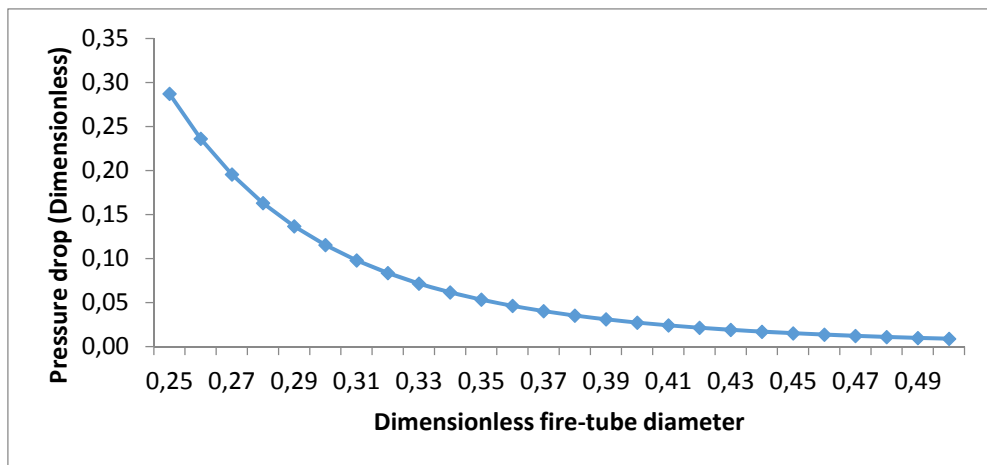

Fig. 2. Pressure drop in fire-tube as a function of diameter.

5.2. Effects of fire-tube pressure drop on entropy generation, at dimensionless length of 2.5

Figure 3 shows the relationship between pressure drop in the fire-tube and entropy generation number. Pressure drop in the fire-tube has a significant effect on entropy generation rate in the system. The increase in fire-tube pressure drop increases entropy generation in the system.
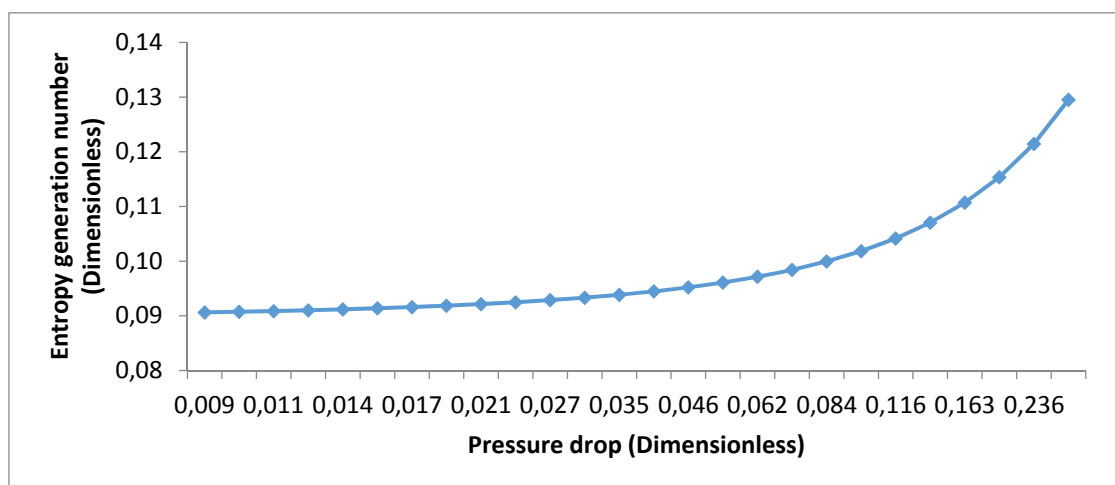

Fig. 3. Entropy generation number as a function of pressure drop.

5.3. Effects of fire-tube diameter on entropy generation
Figure 4 presents the effect of dimensionless fire-tube diameter on entropy generation in the system. As it would be expected, increasing fire-tube diameter lowers entropy generation in the unit. This shows that in order to minimize entropy in the heat exchanging unit of a fire-tube steam boiler, it is required to keep the fire-tube diameter as large as possible. Doing this would reduce pressure drop in fire-tube, which in turn minimizes entropy generation rate and hence irreversibility in the system. The result is in agreement with Assad and Oztop [24], where they reported that entropy generation rate decreases with increasing radius.
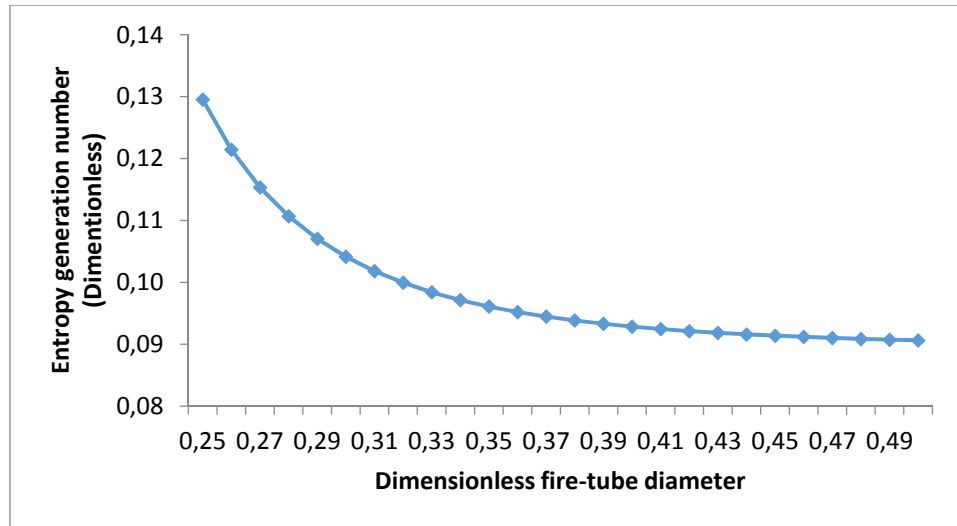

Fig. 4. Entropy generation number as a function of fire-tube diameter.

5.4. Effects of fire-tube length on pressure drop
Conversely, L_t was varied between 0.50 and 5.00 at interval 0.2, while keeping $đ_t$ constant at 0.35. Values for N_s that correspond to each L_t within the range of variation were also obtained in the same way as mentioned above. Figure 5 shows the relationship between dimensionless length of the fire-tube and pressure drop. The pressure drop in fire-tube increases in direct proportion to the length, giving a linear graph. As aforementioned, it is often required to specify a maximum allowable value of pressure drop during heat exchanger design. It is also shown here that pressure drop has significant effect on the level of irreversibility in a system.
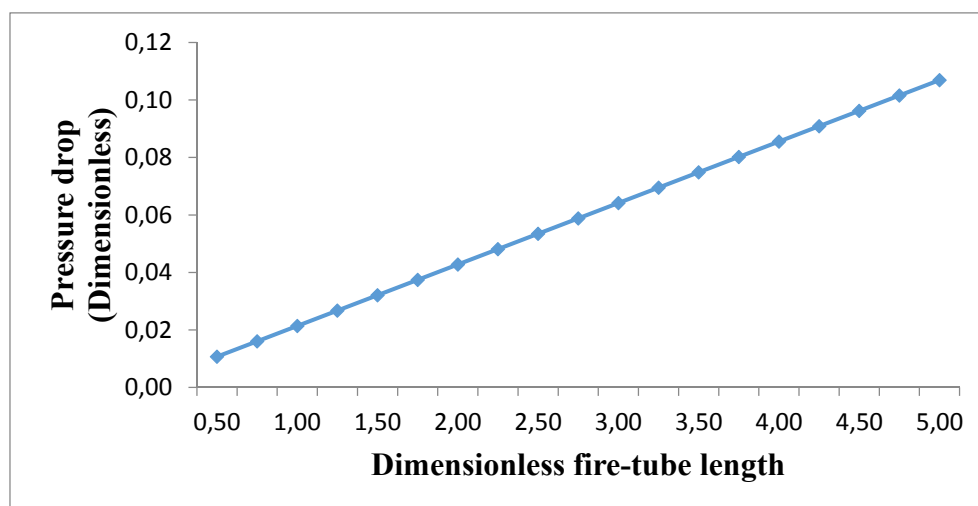

Fig. 5. Pressure drop in fire-tube as a function of length.

5.5. Effects of fire-tube pressure drop on entropy generation, at constant dimensionless diameter of 0.35
Figure 6 shows the relationship between pressure drop in the fire-tube and entropy generation number. Pressure drop in the fire-tube has a linear relationship with entropy generation rate in the system. The increase in fire-tube pressure drop increases entropy generation in a direct proportion. This corroborates the explanations in section 5.2.
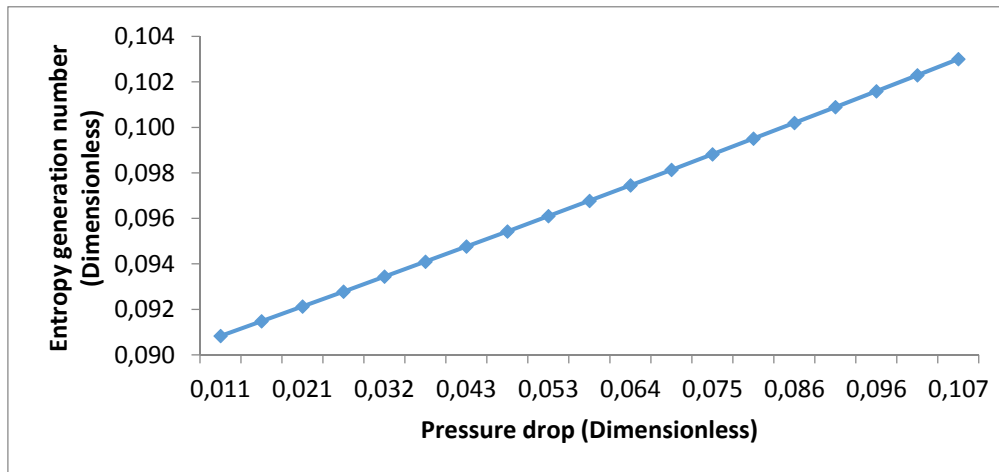

Fig. 6. Entropy generation number as a function of pressure drop.

5.6. Effects of fire-tube length on entropy generation
The linear relationship between dimensionless fire-tube length and entropy generation rate in the system is presented in Figure 7. It reveals that increasing fire-tube length results in a proportional increase in entropy generation in the unit, as it would be expected. This result is comparable with that obtained by Sciubba [25], which reported that lowering aspect ratio minimizes entropy.
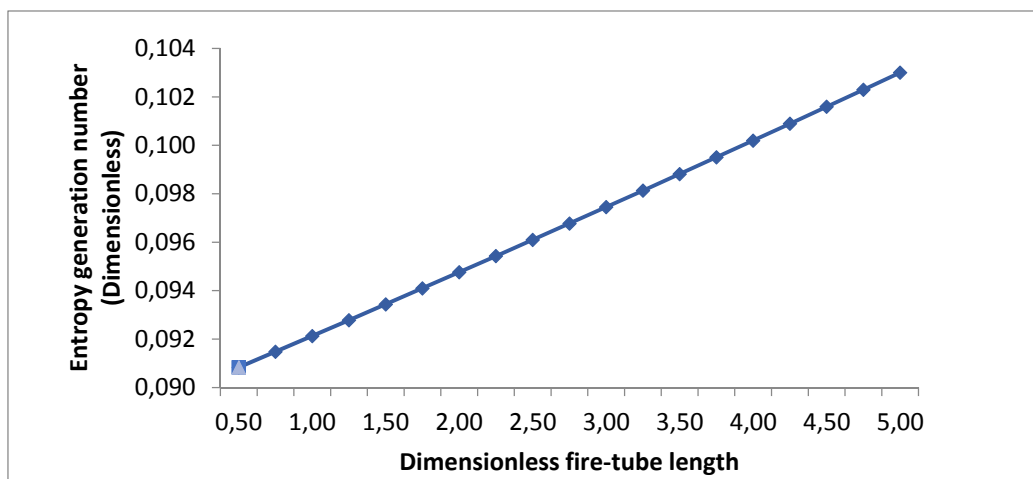

Fig. 7. Entropy generation number as a function of fire-tube length.

It shows that in order to minimize entropy in the heat exchanging unit of a fire-tube steam boiler, it is required to keep the fire-tube as short as possible. Doing this would reduce pressure drop in fire-tube, which in turn minimizes entropy generation rate and hence irreversibility in the system. During design of a fire-tube steam boiler heat exchanger, much attention should be given to the length of fire-tube, since it has direct variation with allowable pressure drop and entropy generation rate in the system. The minimum length that satisfies all requirements should be used in design, for optimum performance of the system.

5.7. Dimensionless fire-tube diameter and dimensionless length, for Entropy Generation Minimization
Having investigated the effects of each of fire-tube length and diameter on entropy generation rate in the system, it is required to study the relationship between fire-tube diameter and length with respect to minimum entropy.

Dimensionless fire-tube diameter was varied between 0.25 and 0.40, and the corresponding values of dimensionless fire-tube length that gave minimum entropy within the maximum volume constraint were obtained. The relationship is shown in Figure 8. The dimensionless fire-tube length increases exponentially with increase in dimensionless diameter. From the result presented in Figure 8, a correlation equation for Entropy Generation Minimization in the fire-tube boilers' heat exchanging unit was obtained and is given by:

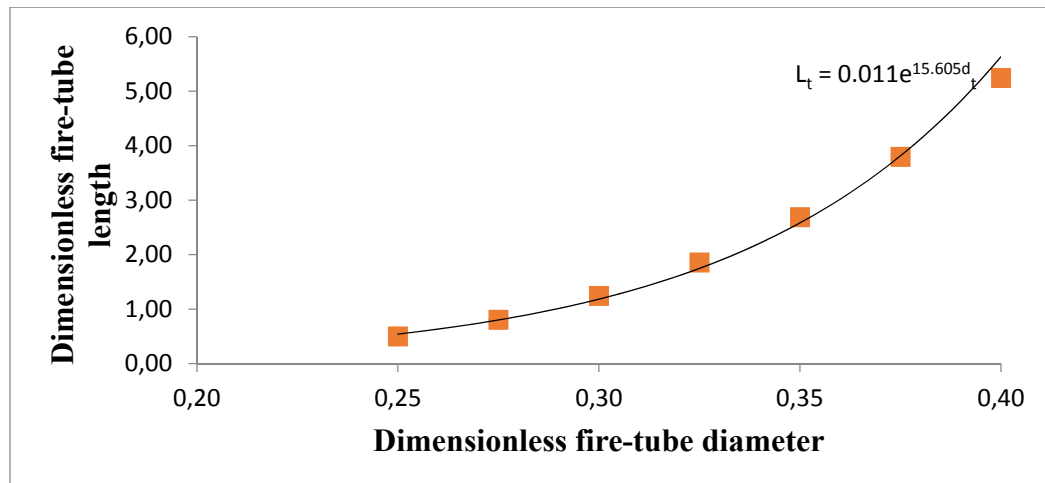$$L_t = 0.011e^{15.60 d_t} \tag{16}$$

Fig. 8. Relationship between dimensionless fire-tube diameter and dimensionless length that minimizes entropy.

6. CONCLUSIONS

The effects of geometric parameters on entropy generation in fire-tube steam boiler's heat exchangers have been investigated. A mathematical equation representing entropy generation rate in the system was developed, and the entropy generation number was determined using appropriate scaling technique. In addition, relationship between entropy generation and geometric features of the heat exchanging unit was obtained. Parametric study showed that pressure drop in the fire-tube and entropy generation in the heat exchanging unit decrease with increasing fire-tube diameter. Conversely, increasing fire-tube length results in proportional increase in both the pressure drop and entropy generation in the unit. This study has contributed to knowledge by establishing a geometry-based correlation equation for entropy generation minimization in the fire-tube boilers' heat exchangers. If well incorporated, this correlation equation would enhance the design of fire-tube steam boilers' heat exchangers.

Nomenclature	
T	Temperature (K)
P	Pressure (Pa)
Q_l	Heat loss (J)
C	Capacity flow rate (WK^{-1})
c_p	specific heat capacity at constant pressure (J/kg K)
R	Gas rate constant (J/kg K)
$\dot{S}_{gen}$	Entropy generation rate (W/K)
Re	Reynolds number
Ns	Entropy generation number
$\dot{P}$	Dimensionless pressure
$\dot{T}$	Dimensionless temperature
P_a	Atmospheric pressure (Pa)
k	constant, ratio of gas rate constant to specific heat capacity at constant pressure
y	constant, ratio of maximum to minimum capacity flow rates
L_s	Length of water shell (m)
d_s	Diameter of water shell (m)

L_t	Length of fire tube (m)
d_t	Diameter of fire tube (m)
V	Volume of fire tube (m^3)
f	Friction factor
N_p	Number of tube passes
N_t	Number of tubes
A_t	Total area of tubes (m^2)
ρ	Density of fluid flowing through the tubes (kg/m^3)
G	Mass velocity of fluid flowing through the tubes (kg/m^2s)
r_{fa}	Actual air fuel ratio
$\tilde{d}_t$	Dimensionless fire-tube diameter
$\tilde{L}_t$	Dimensionless fire-tube length
$\tilde{d}_s$	Dimensionless water-shell diameter
$\tilde{L}_s$	Dimensionless water-shell length
$\Re$	Characteristic number of a fuel
$\mathcal{J}_0$	Characteristic number of a fuel
$\mathcal{J}_1$	Characteristic number of a fuel
$\mathcal{J}_2$	Characteristic number of a fuel
Subscripts	
c	cold fluid
h	hot fluid
gen	generation
p	hot product
w	water
g	exhaust flue gas
s	steam

REFERENCES

[1] Rajput, R.K., A Textbook of engineering thermodynamics, 4th Ed. Laxmi Publications (P) Ltd, New Delhi, 2010.

[2] Giangaspero, G., Sciubba, E., Application of the entropy generation minimization method to a solar heat exchanger: A pseudo-optimization design process based on the analysis of the local entropy generation maps, in ECOS 2012, Proceedings of the 25th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Perugia, Italy, June 26-29, 2012, p. 357-1 - 357-20.

[3] Bejan, A., Entropy generation minimization, CRC Press, Boca Raton, 1996.

[4] Bejan, A., Fundamentals of exergy analysis, entropy generation minimization, and the generation of flow architecture, Int. J. Energy Res., vol. 26, 2002, p. 545-565.

[5] Ordóñez, J.C., Bejan, A., Entropy generation minimization in parallel - plates counterflow heat exchangers. International Journal of Energy Research, vol. 24, no. 10, 2000, p. 843-864.

[6] Nakonieczny, N., Entropy generation in a diesel engine turbocharging system, Energy, vol. 27, 2002, p. 1027-1056.

[7] Ohijeagbon, I.O., Waheed, M.A., Jekayinfa, S.O., Methodolgy for the physical and chemical exergetic analysis of steam boilers, Energy, vol. 53, 2013, p. 153-164.

[8] Ohijeagbon, I.O., Jekayinfa, S.O., Waheed, M.A., Cumulative exergetic assessment of LPFO utilised steam boilers, Int. J. Exergy, vol. 11, 2012, p.119-135.

[9] Kitto, J.B., Stultz, S.C., Steam: its generation and use, 41st Ed. The Babcock and Wilcox Company, Ohio, USA, 2005.

[10] Saidur, R., Ahamed, J.U., Masjuki, H.H., Energy exergy and economic analysis of industrial boilers, Energy Policy, vol. 38, 2010, p. 2188-2197.

[11] Bejan, A., Entropy generation through heat and fluid flow, Wiley, New York, 1982.

[12] Kim, Y., Lorente, S., Bejan, A., Constructal steam generator architecture, International Journal of Heat and Mass Transfer, vol. 52, 2009, p. 2362-2369.

[13] Kim, Y., Lorente, S., Bejan, A., Steam generator structure: continuous model and design, International Journal of Energy Research, vol. 35, 2011, p. 336-345.

[14] Kim, Y., Lorente, S., Bejan, A., Constructal multi-tube configuration for natural and forced convection in cross-flow, International Journal of Heat and Mass Transfer, vol. 53, 2010, p. 5121-5128.

[15] Kim, Y., Lorente, S., Bejan, A., Distribution of size in steam turbine power plants, International Journal of Energy Research, vol. 33, 2009, p. 989-998.

[16] Oyekale, J.O., Entropy generation minimization in the heat exchanging unit of steam boiler, LAUTECH, Ogbomoso, Nigeria, 2015.

[17] Vargas, J.V.C., Bejan, A., Thermodynamic optimization of finned cross flow heat exchangers for aircraft environmental control systems, Int. J. Heat and Fluid Flow, vol. 22, 2001, p. 657-665.

[18] Alebrahim, A., Bejan, A., Entropy generation minimization in a ram-air cross flow heat exchanger, International Journal of Applied Thermodynamics, vol. 2, no. 4, 1999, p. 145-157.

[19] Patel, S.K., Mavini, A.M., Shell and tube heat exchanger thermal design with optimization of mass flow rate and baffle spacing, International Journal of Advanced Engineering Research and Studies, vol. 2, no. 1, 2012, p. 130 - 135.

[20] Ohijeagbon, I.O., Waheed, M.A., Jekayinfa, S.O., Opadokun, O.E., Developmental design of a laboratory fire-tube steam boiler,"ACTA TechnicaConveniensis – Bulletin of Engineering, Tome VI (Year 2013) – FASCICULE (January – March), 2013.

[21] Rogers, G.F.C., Mayhew, Y.R., Thermodynamic and transport properties of fluids. Basil Blackwell, Oxford, 1981.

[22] Guah, A., An efficient generic method for calculating the properties of combustion products, Proc. Instn. Mech. Engrs., vol. 215(A), 2000, p. 375-387.

[23] Holman, J.P., Heat Transfer, 9th Ed. McGraw-Hill, USA, 2002.

[24] Assad, M.E., Oztop, H.F., Parametric study of entropy generation in a fluid with internal heat generation between two rotating cylinders subjected to convective cooling at the surface, International Scholarly Research Network, doi:10.5402/2012/941587.

[25] Sciubba, E., Entropy generation minimization as a design tool. Part 1: analysis of different configurations of branched and non-branched laminar isothermal flow through a circular pipe, International Journal of Thermodynamics, vol. 14, no. 1, 2011, p. 11-20.