Conference of the International Journal of Arts & Sciences,
CD-ROM. ISSN: 1943-6114 :: 09(02):1–12 (2016)

THE HEAT TRANSFER ANALYSIS OF PLATE-FIN HEAT EXCHANGER USED FOR ENERGY RECOVERY APPLICATION: A CASE STUDY

Ali Celen, Emre Aslan, Pınar Celen, Alican Çebi and Ahmet Selim Dalkılıç

Yildiz Technical University, Turkey

Plate-fin heat exchangers are used energy recovery applications because of their compact size and high heat transfer performance. In this study, a plate-fin heat exchanger having offset strip fins is designed in order to heat outside air which can be used another process by using exhaust gas of boiler. Since inlet temperatures are known, ε-NTU method is used in the calculations. The effects of exhaust gas and air mass flow rates on heat transfer coefficient, heat exchanger effectiveness, outlet temperatures and pressure drop is studied by means of the Engineering Equation Solver Software. The best heat exchanger operation conditions are determined by considering efffectiveness calculations.

Keywords: Energy recovery, Effectiveness, Plate-fin heat exchanger design.

Introduction

Heat exchangers can be defined as a device which transfer energy of fluids having different temperatures. Heat exchangers are used variety applications such as waste heat recovery, air conditioning, refrigeration, power production, electronics etc. [1]. Among the other type of heat exchagers, plate-fin heat exchanger very popular because of their high effectiveness (up to 95%), low weight per unit heat transfer, their high surface compactness, large heat transfer surface per unit volume etc. [2]

Dong et al. [3] investigated the effect offset fin geometries (such as fin space, fin height, fin strip length and fin length) on heat transfer performance by using nine different fin geometry. They observed that the heat transfer coefficient and pressure drop are increased with decreasing fin height. Moreover, the heat transfer coefficient and pressure drop are increased with increasing fin strip length. According to their results, fin strip length and fin space have significant effect on heat exchanger performance.

Kuchhadiya and Rathod [4] conducted an experimental study in order to determine performance of cross flow plate fin heat exchanger having offset strip fin. The variation of the effectivess with heat transfer coefficient and fluid velocity is investigated. They compared experimental heat transfer coefficient results with the correlation given in the literature.As a results of the study, they produced the correlation for colburun factor to estimate heat transfer coefficient.

Michna et al. [5] investigated the heat transfer characterictics of offset fin strip for higher Reynolds number conditions.Their results showed that available correlations for heat transfer coefficient and pressure drop prediction of offset strip fin are not suitable for higher Reynolds number conditions because of turbulent flow and vortex shedding.

Dong et al. [6] experimentally studied the heat transfer characteristics of air flowing in offset strip fin and flat tube heat exchangers.They conducted experiment with sixteen offset strip fins having different geometrical parameters.They stated that the heat transfe coefficient and pressure drop is increased with decreasing fin space, fin length and fin height.Moreover, they proposed Colburn j-factor and Fanning fraction f-factor correlations for estimation heat transfer coefficient and friction factor and compared them with correlations given in the literature.

In this study, a plate-fin heat exchanger is designed for heating outside air by using exhaust gas. The schematic representation of heat exchanger can be seen in Figure 1. The parameters for working conditions (mass flow rate and temperature) and surface geometry (fin thickness, fin distance, fin pitch, plate thickness, fin offset length, heat exchanger size) are assumed and they can be seen in Table 1. The influence of inlet temperature and mass flow rate of fluids (exhaust gas and air) on heat transfer coefficient, heat exchanger effectiveness, outlet temperatures and pressure drop is studied by using Engineering Equation Solver (EES) [7].

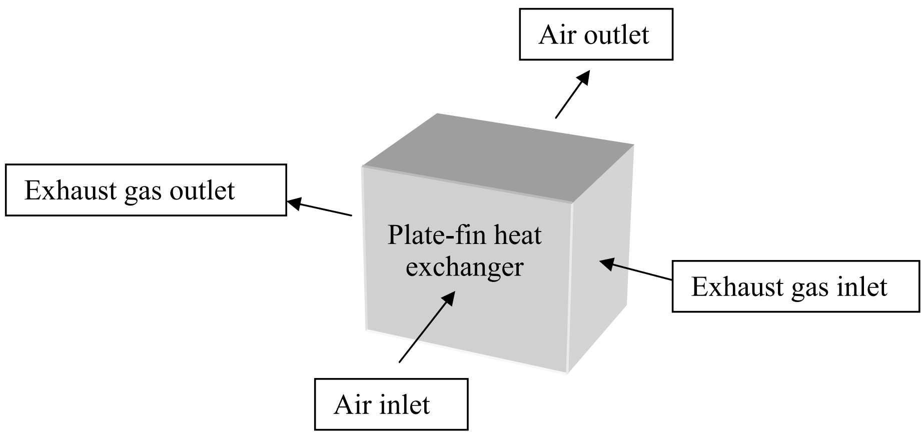


Figure 1. Schematic representation of plate-fin heat exchanger

Table 1. Assumed parameters for design of heat exchanger

Parameter	Value
Air inlet temperature	25°C
Air mass flow rate (m_a)	1-1,2-1,4 kg/s
Exhaust gas inlet temperature ($T_{g,i}$)	200 °C -300 °C
Exhaust gas mass flow rate (m_g)	1-1,5,-2 kg/s
Distance between plates is assumed as (b)	0.003 m
Hydraulic diameter is assumed (D_h)	0.002 m
Thermal conductivity of plates (k)	18 W/m^{2}K
Fin thickness (δ)	0.00015m
Fin distance (s)	0,001
Fin pitch (p_f)	0,00115
Plate thickness (a)	0.0005 m
Fin offset length (l_s)	0.005 m
Compactness (β)	2500
Overall size of heat exchanger 1 (X*Y*Z) Overall size of heat exchanger 2 (X*Y*Z)	0.2 m *0.2 m* 0.2 m 0.35m *0.35m*0.35m

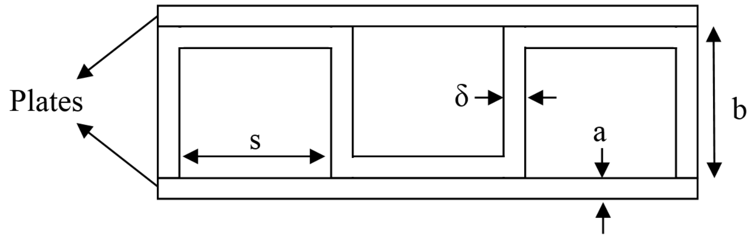


Figure 2. Schematic representation the dimensions of offset strip fin [1]

Calculation Method

Since outlet temperatures are unknown ε-NTU method is selected for design of heat exchanger. Plate-fin heat exchanger design methodology is obtained from [8]. Firstly, effectivess is assumed and outlet temperatures for air and exhaust gas are calculated by using equation below according to assumed effectiveness.

$$T_{ao,assumed} = T_{a,i} + \varepsilon_{assumed} \frac{m_g}{m_a} (T_{g,i} - T_{a,i}) \quad (1)$$

$$T_{go,assumed} = T_{g,i} - \varepsilon_{assumed} (T_{g,i} - T_{a,i}) \quad (2)$$

Number of passage is calculated as follows:

$$Z = Nb_g + (N+1)b_a + (2N+2)\delta_w \quad (3)$$

Heat exchanger volume between plates is estimated as follows:

$$V = XYbN \quad (4)$$

Heat exchanger area is calculated as follows:

$$A = \beta V \quad (5)$$

The minimum free-flow area is then calculated as follows:

$$A_{ffa} = \frac{D_h A}{4X} \quad (6)$$

Reynolds number for air and exhaust gas sides are calculated as follows:

$$Re = \frac{\dot{m}}{A_{ffa}} \frac{D_h}{\mu} = G \frac{D_h}{\mu} \quad (7)$$

The heat transfer coefficient of air and exhaust gas calculated as follows:

$$h = \frac{jGc_p 10^3}{Pr^{(2/3)}} \quad (8)$$

where ja and jg is estimated by using the correlation of Manglik and Bergles [4] for both air and exhust gas

$$j = 0.6522 Re^{-0.5406} \left(\frac{s}{h'}\right)^{-0.1541} \left(\frac{\delta}{l_s}\right)^{0.1499} \left(\frac{\delta}{s}\right)^{-0.0678} \left[1 + \frac{5.269}{100000} Re^{1.340} \left(\frac{s}{h'}\right)^{0.504} \left(\frac{\delta}{l_s}\right)^{0.456} \left(\frac{\delta}{s}\right)^{-1.055}\right]^{0.1} \quad (9)$$

The overall fin efficiencies are calculated as follows:

$$\eta = 1 - (1 - \frac{\tanh(m\ell)}{(m\ell)})\frac{A_f}{A} \tag{10}$$

where fin parameter m is determined as follows:

$$m = \left(\frac{2h}{k_f \delta}(1 + \frac{\delta}{\ell_s}) \right)^{1/2} \tag{11}$$

UA is estimated as follows:

$$\frac{1}{UA} = \frac{1}{\eta_{o,g} h_g A_g} + R_w + \frac{1}{\eta_{o,a} h_a A_a} \tag{12}$$

NTU is estimated as follows:

$$NTU = \frac{UA}{C_{min}} \tag{13}$$

where Cmin is lower heat capacity of fluids.

ε_{final} is calculated by means of equation given below [10]:

$$\varepsilon_{final} = 1 - \exp\left[\frac{NTU^{0.22}}{C_r} \left\{ \exp\left[-C_r (NTU)^{0.78} \right] - 1 \right\} \right] \tag{14}$$

$$C_r = \frac{C_{min}}{C_{max}} \tag{15}$$

Iteration process is started between εassumed and εfinal until it is converged.The converge value of ε is called εactual in the study.

$$q = \varepsilon_{actual} (T_{g,i} - T_{a,i}) C_{min} \tag{16}$$

The outlet temperatures for exhaust gas and air are determined by using equations below, respectively.

$$T_{g,o} = T_{g,i} - \frac{q}{C_g} \tag{17}$$

$$T_{a,o} = T_{a,i} - \frac{q}{C_a} \tag{18}$$

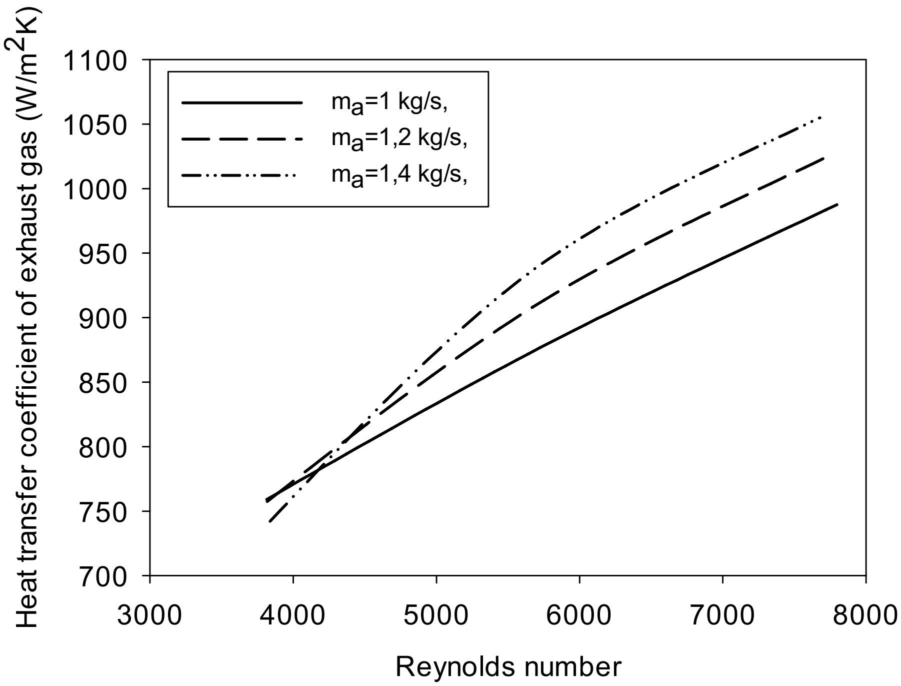
Core pressure drop of heat exchanger is calculated as follows:

$$\Delta P_{core} = \frac{G^2}{2g\rho_i} \left[2\left(\frac{\rho_i}{\rho_o} - 1 \right) + f \frac{X}{r_h} \frac{\rho_i}{\rho_m} \right] \tag{19}$$

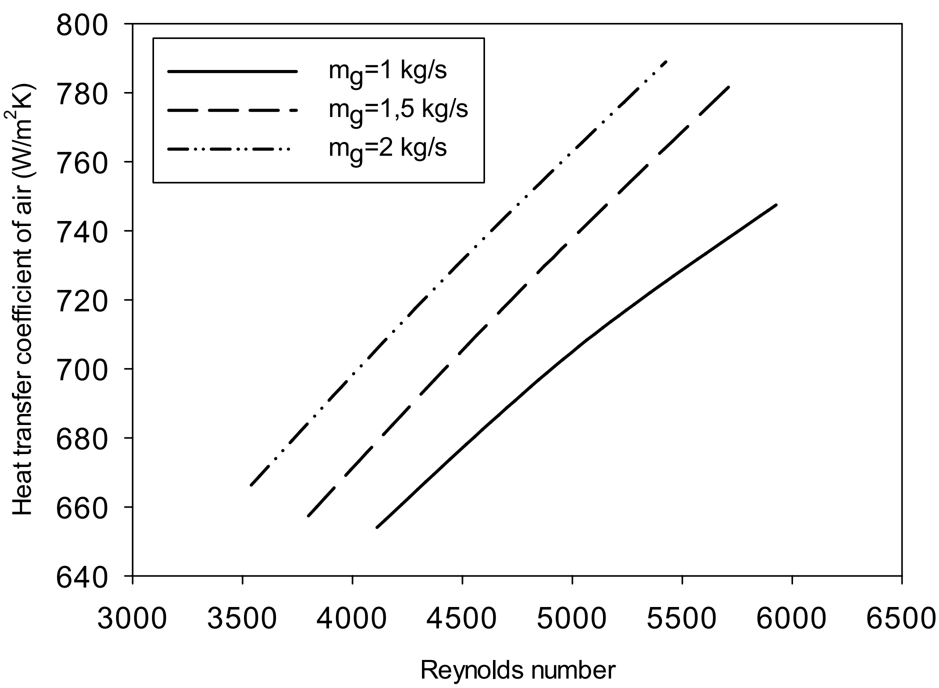
The friction factor is calculated by means of Manglik and Bergles correlation [9] as follows:

$$f = 9.6243 Re^{-0.7422} \left(\frac{s}{h^{1}} \right)^{-0.1856} \left(\frac{\delta}{l_s} \right)^{0.3053} \left(\frac{\delta}{s} \right)^{-0.2659} \left[1 + \frac{7.669}{10^8} Re^{4.429} \left(\frac{s}{h^{1}} \right)^{0.92} \left(\frac{\delta}{l_s} \right)^{3.767} \left(\frac{\delta}{s} \right)^{0.236} \right]^{0.1} \tag{20}$$

Results and Discussion

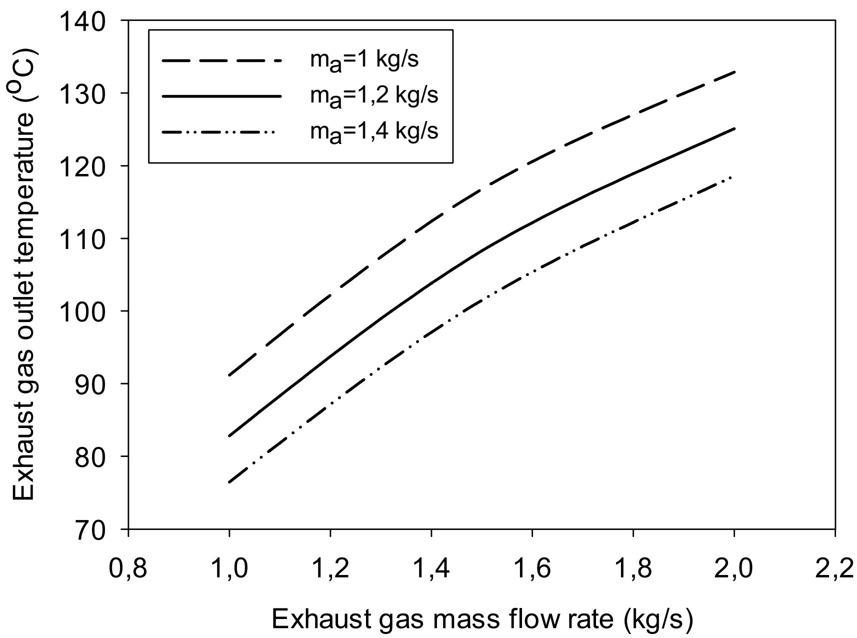


(a)

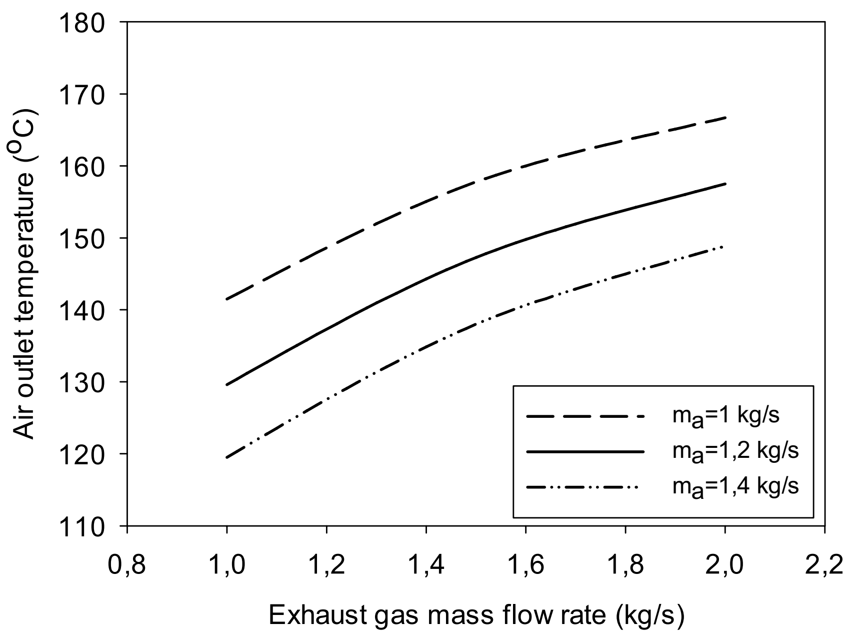


(b)

Figure 3. The variation of heat transfer coefficient with Reynolds number for $T_{g,i}$=200°C, $T_{a,i}$=25° C a) for different air mass flow rates b) for different exhaust gas mass flow rates



(a)



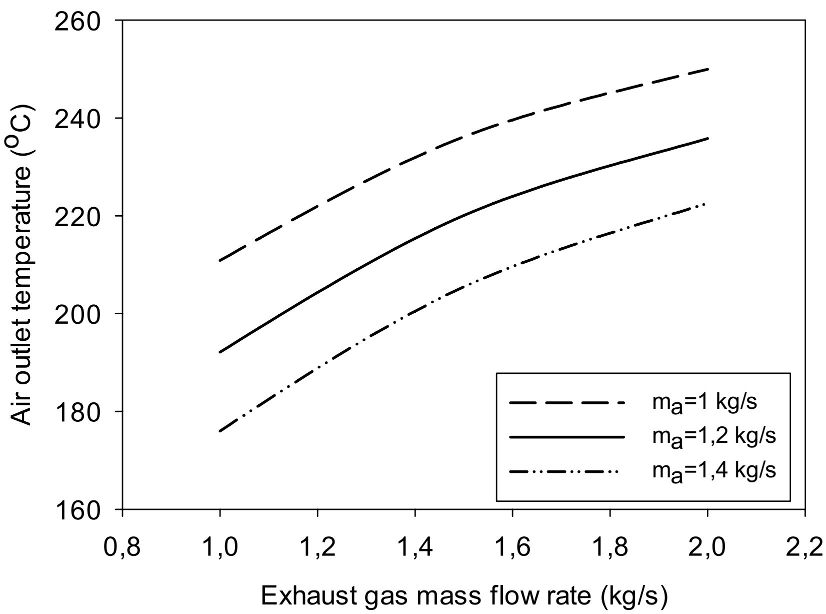
(b)

Figure 4. The variation of outlet temperatures for $T_{g,i}$=200°C, $T_{a,i}$=25° C a)exhaust gas b)air

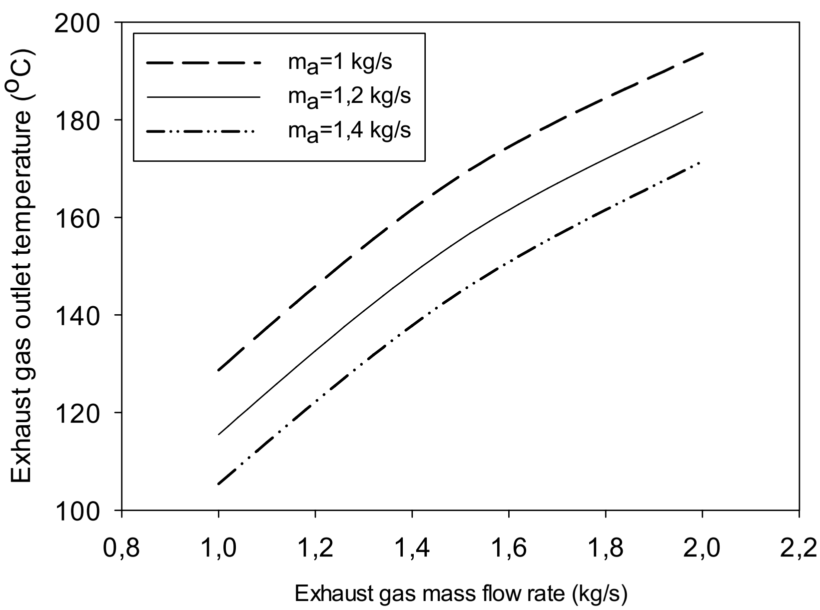
Figure 3 (a) and (b) shows variation of heat transfer coefficient of exhaust gas and air with Reynolds number for different mass flow rates, respectively.The heat transfer coefficient for both fluid is estimated by using Eq. (8). It can be observed that the maximum heat transfer coefficient is obtained for the highest mass flow rate which are 1.4 kg/s and 2 kg/s for air and exhaust gas flow rates, respectively.

Figure 4 (a) and (b) represents the variation of exhaust gas and air outlet temperatures with mass flow rate for exhaust gas inlet temperatures of 200°C and air inlet temperature of 25°C. The exhaust and air outlet temperatures are estimated by using Eq. (17) and (18), respectively. The lowest exhaust outlet temperature is observed as 77°C for air mass flow rate of 1.4 kg/s and exhaust gas mass flow rate of 1 kg/s. Moreover, the highest air outlet temperature is observed as 167°C for air mass flow rate of 1 kg/s and exhaust gas mass flow rate of 2 kg/s.

Figure 5 (a) and (b) represents the variation of exhaust gas and air outlet temperatures with mass flow rate for exhaust gas inlet temperatures of 300°C and air inlet temperature of 25°C. The exhaust and air outlet temperatures are estimated by using Eq. (7) and (8), respectively. The lowest exhaust outlet temperature is observed as 106°C for air mass flow rate of 1.4 kg/s and exhaust gas mass flow rate of 1 kg/s. Also, the highest air outlet temperature is observed as 250°C for air mass flow rate of 1 kg/s and exhaust gas mass flow rate of 2 kg/s. Also,



(a)



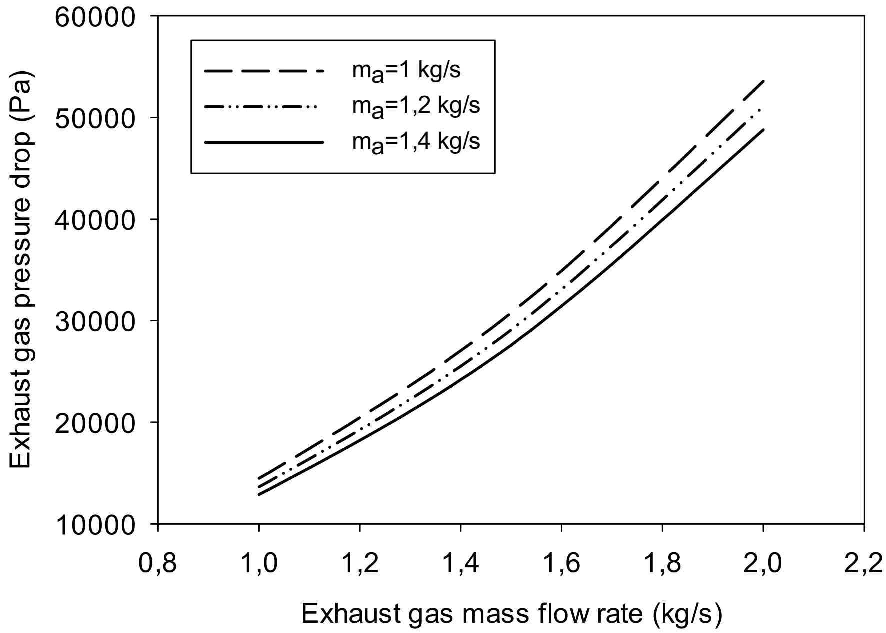
(b)

Figure 5. The variation of outlet temperatures for $T_{g,i}$=300°C, $T_{a,i}$=25° C a)exhaust gas b)air

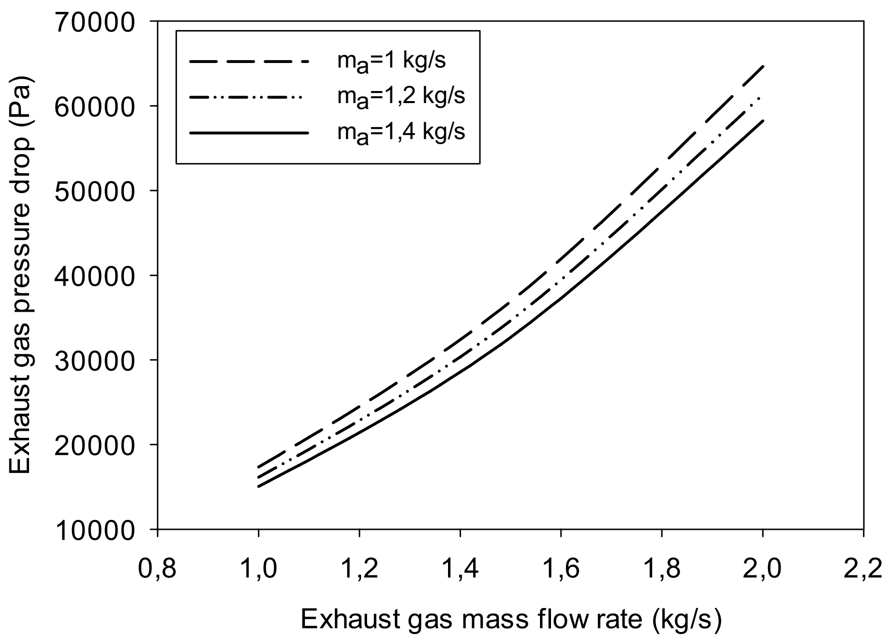
Table 2 depicts comparison of of effectiveness for heat exchanger 1 and 2 in the range of assumed temperatures and mass flow rates. It should be noted that the dimensions of heat exchanger 1 and 2 have 0.2 m x 0.2 mx 0.2 m 0.35 m x 0.35 m x 0.35 m as width, height, and length, respectively. The maximum effectiveness is obtained for minimum air mass flow rate and maximum exhaust gas flow rate for both heat exchangers. It should be noted that effectiveness is increased from 0.81 to 0.94 for exhaust gas inlet temperature of 200°C by extending dimensions of heat exchanger from 0.2 m x 0.2 mx 0.2 m 0.35 m x 0.35 m x 0.35 m. For exhaust gas inlet temperature of 300°C, effectiveness is increased from 0.82 to 0.95 for the same conditions.

Table 2. Comparison of effectiveness for different size heat exchanger

Exhaust gas inlet temperature	Air inlet temperature	Air mass flow rate	Exhaust gas mass flow rate	Effectiveness L=0.2	Effectiveness L=0.35
°C	°C	kg/s	kg/s	-	-
200	25	1	1	0,67	0,80
200	25	1	1,5	0,76	0,90
200	**25**	**1**	**2**	**0,81**	**0,94**
200	25	1,2	1	0,70	0,82
200	25	1,2	1,5	0,67	0,85
200	25	1,2	2	0,76	0,91
200	25	1,4	1	0,71	0,86
200	25	1,4	1,5	0,65	0,80
200	25	1,4	2	0,71	0,88
300	25	1	1	0,68	0,81
300	25	1	1,5	0,77	0,91
300	**25**	**1**	**2**	**0,82**	**0,95**
300	25	1,2	1	0,67	0,82
300	25	1,2	1,5	0,71	0,86
300	25	1,2	2	0,77	0,92
300	25	1,4	1	0,71	0,86
300	25	1,4	1,5	0,66	0,81
300	25	1,4	2	0,72	0,88



(a)

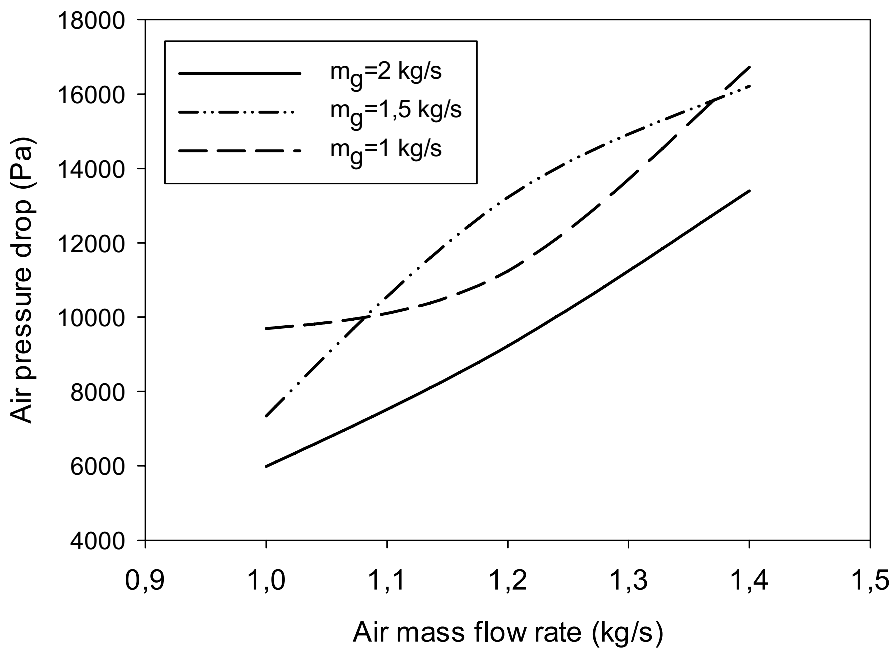


(b)

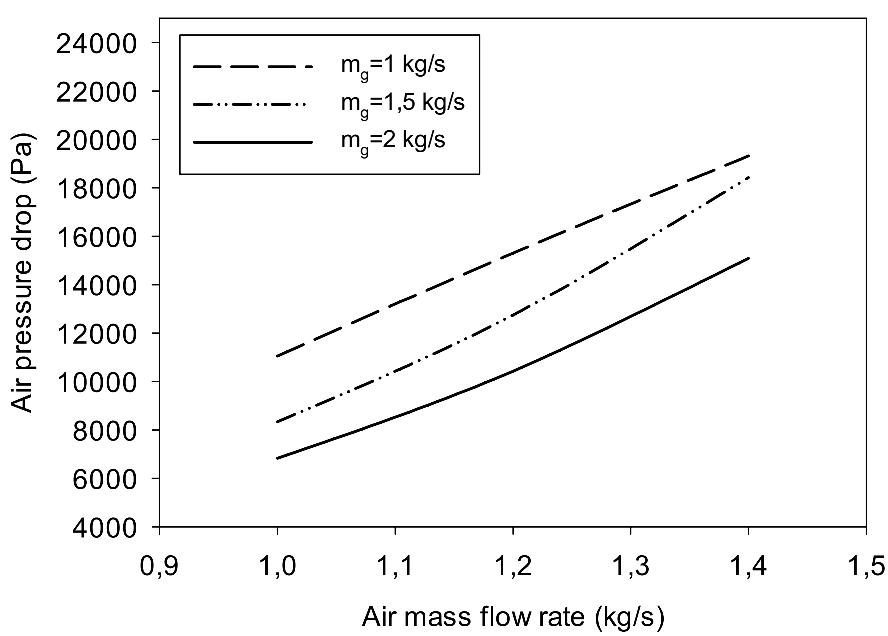
Figure 6. The variation of exhaust gas pressure drop with mass flow rate a) $T_{g,i}$=200°C, $T_{a,i}$=25° C b) $T_{g,i}$=300°C, $T_{a,i}$=25° C

Figure 6 (a) and (b) represents the variation of exhaust gas pressure drop with mass flow rate different exhaust gas inlet temperatures. The pressure drop is calculated by means of Eq. (19). As assumed, the pressure drop is increased with increasing mass flow rate. The maximum pressure drop of exhaust gas is calculated as 53579 Pa and 64654 Pa for exhaust gas inlet temperature of 200°C and 300°C, respectively.

Figure 7 (a) and (b) represents the variation of air pressure drop with mass flow rate different exhaust gas inlet temperatures. The pressure drop is calculated by means of Eq. (19). As assumed, the pressure drop is increased with increasing mass flow rate. The maximum core pressure drop of air is calculated as 16731Pa and 19322 Pa for exhaust gas inlet temperature of 200°C and 300°C, respectively.



(a)



(b)

Figure 7. Exhaust gas pressure drop a) $T_{g,i}$=200°C, $T_{a,i}$=25° C b) $T_{g,i}$=300°C, $T_{a,i}$=25°

Conclusion

In this study, a plate-fin heat exchanger is designed by calculating surface gometries and heat transfer characteristics. The following results are obtained:

- The maximum heat transfer coefficient is obtained for the highest mass flow rate for both fluids.
- The inlet air is heated up to 167°C and 200°C by means of the exhaust gas having inlet temperatures of 200°C and 300°C.
- The exhaust gas is cooled 77°C and 106°C by by means of the air having inlet temperature of 25°C.
- The effectiveness of the heat exchanger is determined by means of the parametric calculations for different working conditions.
- The effectiveness of heat exchanger is increased 16% by enlarging volume of heat exchanger.
- The pressure drop is determined for exhaust gas ans air for considered working conditions.

Nomenclature

a	Plate thickness [m]
A	Heat transfer area [m^2]
A_{ffa}	Minimum free-flow [m^2]
A_f	Fin surcafe araea [m^2]
b	Distance between plates [m]
C_r	Ratio of heat capacities rates
C_a	Heat capacity rates of air [W/K]
C_g	Heat capacity rates of exhaust gas [W/K]
C_{max}	Larger of the two heat capacity rates [W/K)
C_{min}	Smaller of the two heat capacity rates [W/K]
c_p	Specific heat capacity [kJ/kgK]
D_h	Hydraulic diameter [m]
f	Friction factor [-]
G	mass flux [kg/m^2s]
h	Heat transfer coefficient [W/m^2K]
h^{l}	Fin height [m]
j	Colburn factor [-]
k	Thermal conductivity of plates [W/m^2K]
k_f	Thermal conductivity of fin [W/m^2K]
k	Plaka malzemesinin ısıl iletkenliği[W/mK]
l_s	Fin offset length [m]
$\dot{m}_a$	Air mass flow rate [kg/s]
$\dot{m}_g$	Exhaust gas mass flow rate [kg/s]
m	Fin parameter [-]
N	Number of passages for one fluid side [-]
NTU	Number of transfer unit [-]
η	Overall fin efficiency [-]
p_f	Fin pitch [m]
ΔP	Pressure drop (Pa)
Pr	Prandtl number [-]
q	Heat transfer rate [W]
R_w	Thermal resistance [K/W]
Re	Reynolds number [-]
s	Fin spacing [m]
$T_{a.i}$	Air inlet temperature [°C]

$T_{a.o}$	Air outlet temperature [^{o}C]
$T_{ao, assumed}$	Air outlet temperature calculated by assumed effectiveness [^{o}C]
$T_{g.i}$	Exhaust gas inlet temperature [^{o}C]
$T_{g.o}$	Exhaust gas outlet temperature [^{o}C]
$T_{go,assumed}$	Exhaust gas outlet temperature calculated by assumed effectiveness [oC]
U	Overall heat transfer coefficient [W/m^{2}K]
V	Heat transfer voluma for one fluid side [m^3]
X	Width of heat exhanger [m]
Y	Length of heat exhanger [m]
Z	Heigth of heat exhanger [m]

Greek symbols

ε	Effectiveness
β	Compactness [m^2/m^3]
δ	Fin thickness [m]
δ_w	Plate wall thickness [m]
ρ	Density [kg/m^3]
μ	Fluid viscosity (kg/ms)

Subscript

a	air
f	fin
g	exhaust gas
i	inlet
m	mean
o	outlet
w	wall

References

1. S. Kakaç, H. Liu, A. Pramuanjaroenkij Heat Exchangers: Selection, Rating, and Thermal Design, second ed., CRC Press, 2002.
2. K. Thulukkanam, Heat Exchanger Design Handbook, second ed., CRC Press, 2013.
3. J. Dong, J. Chen, Z. Chen, Flow and heat transfer in compact offset strip fin surfaces, Front. Energy Power Eng. China 2 (3) (2008) 291–297.
4. B.B. Kuchhadiyaa, P.P. Rathod, Experimental investigation of thermal behavior of cross flow platefin heat exchanger with offset strip fin, Procedia Technology 23 (2016) 423 – 430.
5. G.J. Michna, A. M. Jacobi, R. L. Burton, Friction factor and heat transfer performance of an offset-strip fin array at air-side reynolds numbers to 100,000, International Refrigeration and Air Conditioning Conference, Purdue, 2006.
6. J. Dong, J. Chen, Z. Chen, Y. Zhou, Air-side thermal hydraulic performance of offset strip fin aluminum heat exchangers, Applied Thermal Engineering 27 (2007) 306–313.
7. Engineering Equation Solver, F-Chart Software, 2015.
8. R. K. Shah, D. P. Sekulic, Fundamentals of Heat Exchanger Design, John Wiley & Sons,2003.
9. R. M. Manglik, A. Bergles, E., Heat transfer and pressure drop correlations for the rectangular offset strip fin compact heat exchanger, Experimental Thermal and Fluid Science, 10 (2) (1995) 171-180.
10. F. P. Incropera, D. P. DeWitt, Fundamentals of Heat and Mass Transfer, fourth ed., Wiley, New York, 2002.