Theoretical Study on Influence of Exhaust Gas and Coolant Flow Rate on Heat Recovery of Engine Exhaust by Using Fin and Tube Heat Exchanger

Sarang Chavan
Department of Mechanical Engineering
K J Somaiya College of Engineering, Vidyavihar, Munbai
sarang.c@somaiya.edu
Contact: +919552665344

Dr. S.S. Bhusnoor
Department of Mechanical Engineering
K J Somaiya College of Engineering, Vidyavihar, Mumbai
siddappabhusnoor@somaiya.edu
Contact: +919920534514

Abstract : Plate fin-and-tube heat exchangers are used extensively in heating, ventilating, and air conditioning as well as in refrigeration systems. Non-uniform inlet air flow distribution has a substantial effect on heat exchanger performance [2]. Efficiency of heat exchanger and its dimensions are one of the most important parameters to consider in engineering design activity.

Various studies were done on find and tube heat exchanger to improve the air side heat transfer coefficient. C. C. Wang (2000) studied the airside performance of fin and tube heat exchangers with plain fin configurations. The effect of the number of tube rows, fin pitch and tube diameter on the thermal- hydraulic characteristics was examined.

Various studies on performance of fin tube heat exchanger are done by researchers. Presently the use of vehicles in transport is growing; in vehicles about 35-40% heat energy is lost in exhaust gas. To recover this heat energy for thermal application we can use the compact heat exchanger as a waste heat recovery system.

This paper includes the literature survey on fin and tube heat exchanger. In this paper theoretical analysis for rating of heat exchanger is carried out along with comparison of literature studies carried out by various researchers.

Keywords: Fin and tube heat exchanger, waste heat recovery.

*****

Nomenclature

A_f	Fin surface area (m^2)
A_o	Total surface area(m^2)
A_{min}	Minimum flow area(m^2)
C_p	Specific heat(kJ/kg °C)
C_r	Heat capacity(W/k)
G_{max}	Mass flux through minimum flow area (kg m^{-2} s^{-1})
h	Convective heat transfer coefficient (W m^{-2} k^{-1})
T	Temperature
$\dot{m}$	Mass flow rate (kg s^{-1})
Q	Heat capacity (W)
U	Overall heat transfer coefficient(W m^{-2} k^{-1})

Greek letters

ε	Effectiveness
η	Efficiency
μ	Dynamic viscosity of the fluid (N s m^{-2})
Δ	Difference

Subscripts

CW	Cooling water
Exh	Exhaust

I. Introduction

Various studies have been conducted on the fin patterns (such as plate, louver, convex-louver, and wavy), fin geometries (such as fin pitches and fin height) and other geometrical parameters to improve the air-side thermal and flow performances of fin and tube heat exchanger. The working fluid was chosen to be water to reduce the cost and time to change coils.

The water side heat transfer and pressure drop behavior inside the tubes is well established and fairly straight forward. In contrast, the air side heat transfer and pressure drop behavior is the subject of countless research studies and is quite complicated. Designers must rely on experimental measurement of these characteristics. Often, air side performance is proprietary. Finned-tube heat exchangers have been tested for at least the last 90 years (Wilson 1915). During that time, advances in technology as well as the efforts of many research engineers has increased the knowledge and availability of air side performance data. The endeavors of D.G. Rich (1973, 1975), F.C. Mc Quiston (1978, 1981), R.L. Webb (1986, 1998), and C.C. Wang (1998a, 1998b, 1998c, 1999, 2000a, 200b) serve as milestones in the road of experimental performance measurement and correlation of the air-side performance.

Rich D. G. (1973) examined the effects of fin spacing and the number of tube rows on the heat transport of several heat exchangers. Varying the number of tube rows from one to six, Rich concluded that, depending upon the Reynolds number, the average heat transfer coefficients for a deep coil may be higher or lower than that for a shallow coil.

The heat exchanger is a basic component that is used for thermal systems in many industrial processes involving heat transfer. The most favorable type of heat exchanger used in industrial applications is the fin and tube heat exchanger. It is very important to consider the heat transfer rate, which is normally limited by the thermal resistance on the air-side of the heat exchanger. One way to augment the heat transfer rate on the air-side of the heat exchanger is to improve the fin geometry [3].

Plate fin-and-tube heat exchangers of plain fin pattern are employed in a wide variety of engineering applications such as air-conditioning apparatus, process gas heaters and coolers. The fin-and-tube heat exchangers usually consist of mechanically or hydraulically expanded round tubes in a block of parallel continuous fins and, depending on the application, the heat exchangers can be produced with one or more rows. There are many variants regarding fin patterns of plate fin-and-tube heat exchangers, e.g. plain, wavy, louver and convex-louver. Among them, plain fin configuration is still the most popular fin pattern, owing to its simplicity, durability and versatility in application [1]

The governing thermal resistance for heat exchangers is typically located on the air side, accounting for 85% or more of the total resistance in practical applications. Consequently, the use of finned surfaces on the air side facilitates improvements to the overall thermal performance of heat exchangers [2].

Heat exchange devices are essential components in complex engineering systems related to energy generation and energy transformation in industrial scenarios. The calculation of convection coefficients constitutes a crucial issue in designing and sizing any type of heat exchange device [4].

Fins are used to increase the effective surface area of heat exchanger tubing. Finned tubes are used when the heat transfer coefficient on the outside of the tubes is appreciably lower than that on the inside.

A. Classification of heat exchanger

Heat exchangers are device that provide the flow of thermal energy between or more fluids at different temperatures. Heat exchangers are used in verity of applications. These includes power production process, chemical and food industries, waste heat recovery, manufacturing industry, air conditioning, refrigeration and space application .

B. Extended surface heat exchangers.

Extended surface heat exchangers are device with fins or appendages on the primary heat transfer surface with object of increasing heat transfer area. The purpose of the extended surface is to reduce the size of heat exchanger.

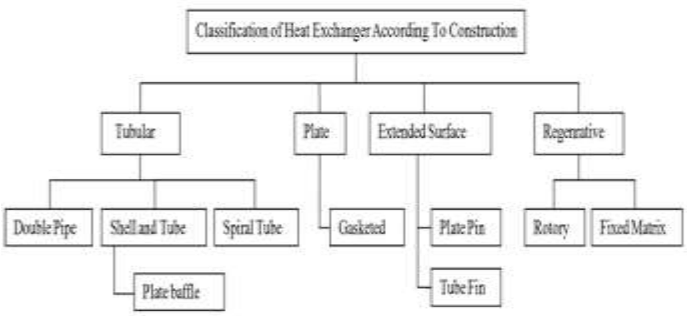

Figure 1 Classification of heat exchanger according to the construction.

C. Fin and tube heat exchanger:

These heat exchangers are used in gas to liquid exchanges. The heat transfer coefficient on the gas side is generally much lower than those on the liquid side and fins are required on gas side.

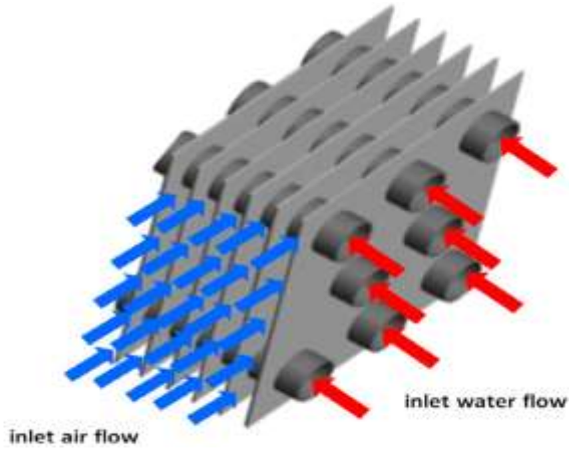

Figure 2 Schematic of typical staggered plain fin-tube compact heat exchanger. (W. Yaïci et al. 2014)

II. Materials and methods

The design of experimental setup is designed to study the performance of fin and tube heat exchanger using exhaust gas as a hot fluid and water as a coolant. Also it is intended to study the effect of mass flow rate of exhaust gas and cooling water on performance fin and tube heat exchanger.

A. Experimental Setup

For conducting the experiment the setup consists the tube and plain fin heat exchanger with staggered arrangement of tube. Thermocouples are used to measure the temperature at various points. Auxiliary heater is provided to heat the exhaust gas to particular temperature. The design parameters of tube and plain fin heat exchanger are provided in table (2).

Designed fin and tube heat exchanger is used to recover the heat from exhaust gas of IC engine. The specifications of engine are given in table (1).

The flow of coolant (water) is varied by the throttle value to examine the performance of fin and tube heat exchanger. Flow of the exhaust gas will be controlled by the suction fan at the exit side of heat exchanger. Inlet temperature of exhaust gas will be changed by using the auxiliary heater to examine effect of inlet temperature of exhaust gas on performance of heat exchanger.

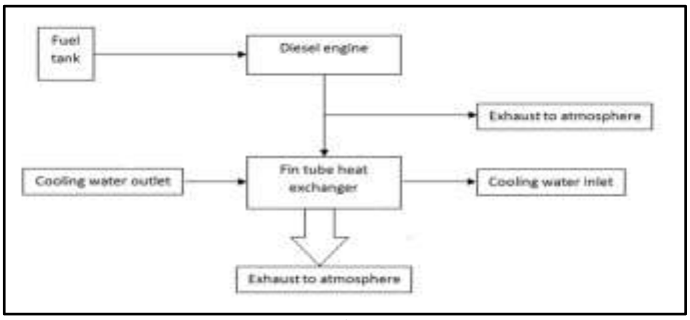

Figure 3 Line diagram of experimental setup.

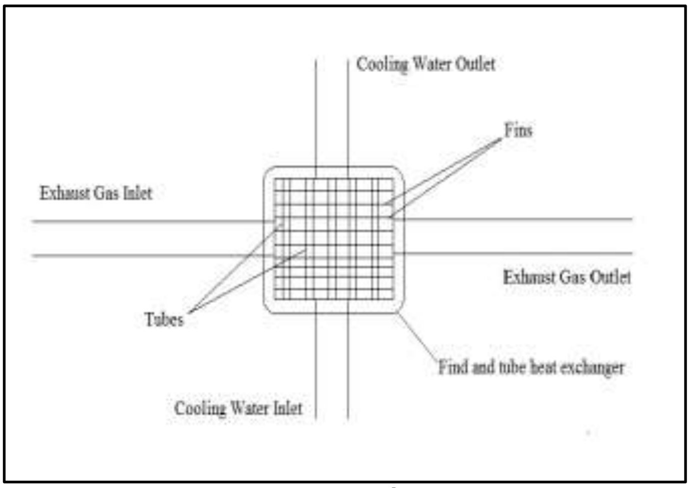

Figure 4 Experimental setup

Table 1 Engine Specifications

Sr.No	Description	Data
1	Name of the Engine Manufacturer	Kirloskar Engine
2	Type of the engine	4-Stroke, Single Cylinder, Vertical, C.I Engine
3	IS Rating	5 H.P at 1500 rpm
4	Bore X Stroke	80mm X 110mm
5	Cubic Capacity	552.64 cc
6	Lubrication	Splash Type
7	Starting	Hand Cranking
8	Fuel Used	Diesel
9	Capacity of Diesel Tank	7 Litre
10	Cooling	Water Cooling

Table 2 Design Parameters of Heat Exchanger

Parameter	Value
Number of tube row	4
Number of tuber per row	4
Tube outside diameter(mm)	10
Tube inside diameter(mm)	8
Tube pitch(mm)	20
Fin thickness(mm)	0.5
Fin pitch(mm)	12.5
Velocity of water (m/s)	0.5
Flue gas flow rate (lpm)	450,400,350,300,250
Inlet temperature of exhaust has	350^0C

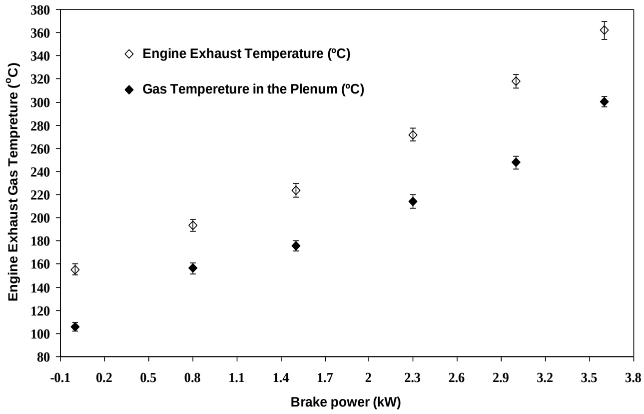

Figure 5 Influence of Engine load on Exhaust gas temperature (Temperatures are measured after the exhaust port and inside the insulated plenum) S.S. Bhusnoor et al. (2016)

Load test on the engine was conducted to confirm the range of exhaust gas temperature at constant speed by S.S. Bhusnoor et al. (2016). Gas temperatures measured after the exhaust valve and at pulse dumper exit are shown in figure 5. These base line measurements were used to set the operating gas temperature and inlet flow rates.

B. Basic Equations

Heat in exhaust gas

$$Q_{Exh} = \dot{m}_{Exh} * C_{pExh} * \Delta T_{Exh} \quad (1)$$

Heat carried away by cooling water

$$Q_{CW} = \dot{m}_{CW} * C_{pCW} * \Delta T_{CW} \quad (2)$$

Heat balance

Heat lost b y exhaust gas = Heat gain by cooling water

$$(\dot{m}_{Exh} * C_{pExh} * \Delta T_{Exh}) = (\dot{m}_{CW} * C_{pCW} * \Delta T_{CW}) \quad (3)$$

For any heat exchanger, the total heat rejected from the hot fluid, exhaust gas, to the cold fluid, water, is dependent on the heat exchanger effectiveness and the heat capacity of each fluid.

$$Q = \varepsilon * C_{min} (T_{Exh,in} - T_{CW,in}) \quad (4)$$

The heat capacity, C, the extensive equivalent of the specific heat, determines the amount of heat a substance absorbs or rejects per unit temperature change.

$$C = m * C_p \quad (5)$$

For a cross-flow heat exchanger with both fluids unmixed, the effectiveness can be related to the number of transfer units (NTU) with the following equation:

$$\varepsilon = 1 - exp\left[\left(\frac{1}{C_r}\right)(NTU)^{0.22}\{exp[-C_r(NTU)^{0.78}] - 1\}\right] \quad (6)$$

Where: Cr = heat capacity ratio

$$C_r = \frac{C_{min}}{C_{max}} \quad (7)$$

The NTU is a function of the overall heat transfer coefficient.

$$NTU = \frac{UA}{C_{min}} \quad (8)$$

The overall heat transfer coefficient, neglecting the wall resistance and the fouling factors

$$UA = \left(\frac{1}{\eta_o h_{Exh} A_{Exh}} + \frac{1}{h_{Cw} A_{CW}}\right) \quad (9)$$

To find the overall surface efficiency for a finned tube heat exchanger, it is first necessary to determine the efficiency of the fins alone. The total air side surface efficiency is given by,

$$\eta_o = 1 - \frac{A_f}{A_o}\left(1 - \eta_f\right) \quad (10)$$

Colburn factor,

$$j = St * Pr^{2/3} \quad (11)$$

Convective heat transfer coefficient in terms of Colburn factor

$$h_{EG} = \frac{j * C_p * G_{max}}{Pr^{2/3}} \quad (12)$$

$$G_{max} = \frac{m}{A_{min}} \quad (13)$$

$$Re = \frac{G_{max} * D_o}{\mu_a} \quad (14)$$

Table 3 Summary of correlations used by researches to find out the heat transfer coefficient using the term Colburn factor.

Sr. no	**Reference**	**Correlations Used to find colburn factor (j)**
1	Kayansayan N ,1993	$j = 0.15Re^{-0.28} \in^{-0.362}$, where $\in$ = (total heat transf er area / bare tube heat transfer area), Valid for $500 \le Re \le 30000$
2	Wang et al.,1996	$j = 0.394Re_c^{-0.392}(t_f/D_c)^{-0.0449} N_r^{-0.0897}(S_f/D_c)^{-0.212}$, Valid for $800 \le Re \le 7500$
3	Wang et al., 2000	$j= 0.086 Re_c^{P3} N^{P4} (S_f/D_c)^{P5} (S_f/ D_h)^{P6} (S_f/ S_t)^{-0.93}$ where: $P3 = -0.361 - 0.042N /ln(Re_c) + 0.158 ln(NS_f/D_t)^{0.41}$ $P4 = -1.224 - 0.076(S_l/D_h)^{1.42} /ln(Re_c)$ $P5 = -0.083 + 0.058N /ln(Re_c)$ $P6 = -5.735 + 1.211(ln(Re_c)/ N)$ $Dh = 4(A_cL/A_o)$, L is the depth of the heat exchanger along the flow direction.
4	Pirompugd et al. ,2005	$j= 1.49^{Re0.002061N-0.625} N^{-0.0575} (0.00583Nr + 0.825)\varepsilon^{-0.001921N+0.068}$ where: ε =(total heat transfer area/ bare tube heat transfer area)
5	Xie et al. ,2009	$Nu = 1.565Re^{0.3414} (N S_f/D)^{-0.165} (S_t/S_l)^{-0.0558}$, Valid for: Re = 1000 − 6000.
6	Choi et al.,2010	$j_{inline} = 0.8692N^{-0.0981}Re^{-0.5971}(S/D)^{0.0996}(F_s/D)^{-2.1720}$ $j_{staggered} = 1.4534N^{-0.0681}Re^{-0.6722} (S/D)^{0.0652} (F_s/D)^{-0.0058}$ Valid for: Re = 500 – 800, Where F_s is the vertical fin spacing in the paper.
7	Paeng et al, 2010	$Nu_{exp} = 0.049 Re^{0.784}$, $Nu_{num} = 0.097 Re^{0.671}$,Valid for: Re = 1082 − 1649.
8	A. Hussain and D. S. Khudor	$j=0.2675 JP +1.325* 10^{-6}$, $JP=Re^{-0.4}*(A_0/A_t)^{-0.15}$

III. Results and discussion

Figure 6 compares the convective heat transfer coefficient values variation by varying the mass flow rate of exhaust gas for various correlations defines by researchers, keeping the temperature difference at exhaust gas constant. It can be seen that the convective heat transfer coefficient increases with increase in mass flow rate (Reynolds number).

The theoretically determined values of the Colburn j factor plotted against mass flow rate of exhaust gas are displayed in Figure 7. The characteristic dimension of the Reynolds number is the based on the outside diameter of the tube.

Various researchers define the correlations for finding heat transfer coefficient on air side. The comparison of various correlations is shown in Figure 6.

It can be seen from Fig.7 that the j factors of fin and tube heat exchanger decreases with the increasing mass flow rate (Reynolds number).

An increase of tube diameter or fin pitch decreases the heat transfer and pressure drop. The effects of tube pitches are relatively smaller than that of tube diameter and fin pitch.

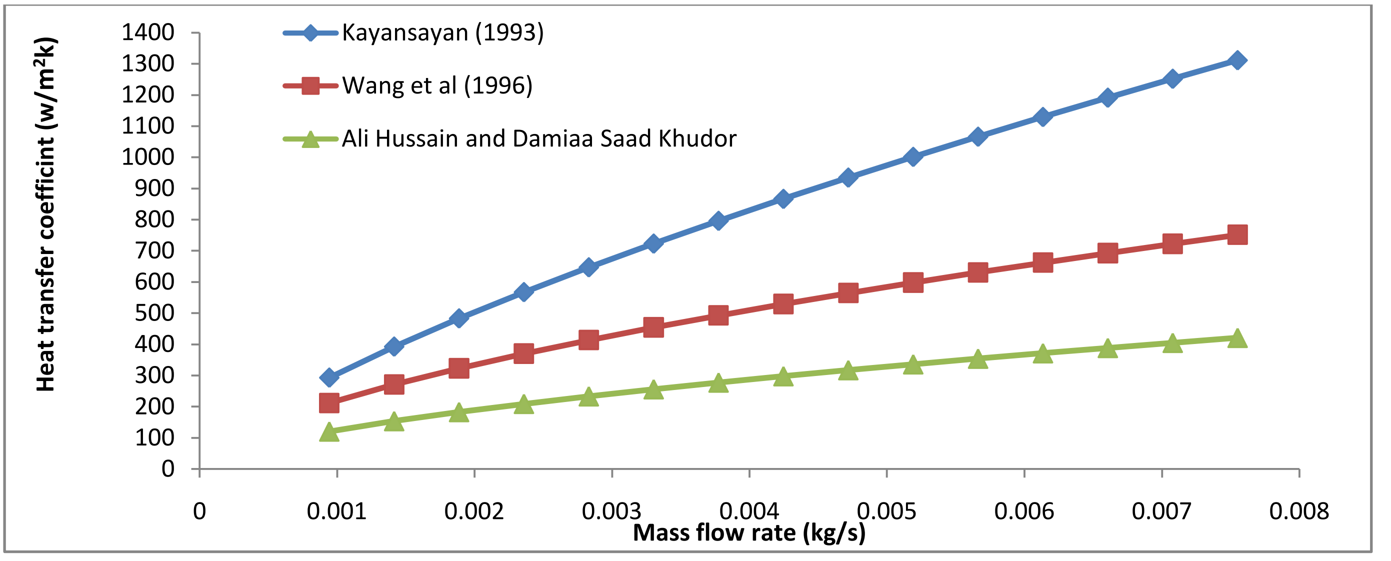

Figure 6 . Comparison of variation in heat transfer coefficient with mass flow rate of exhaust gas by keeping the temperature difference constant for three different correlations.

From the literature it is found that fin thickness and fin spacing has negligible effect on heat transfer characteristics of plate fin and tube heat exchangers.

Figure 8 shows the variation in outlet temperature of cooling water, keeping the mass flow rate of cooling water constant and varying the hot side (exhaust gas) mass flow rate

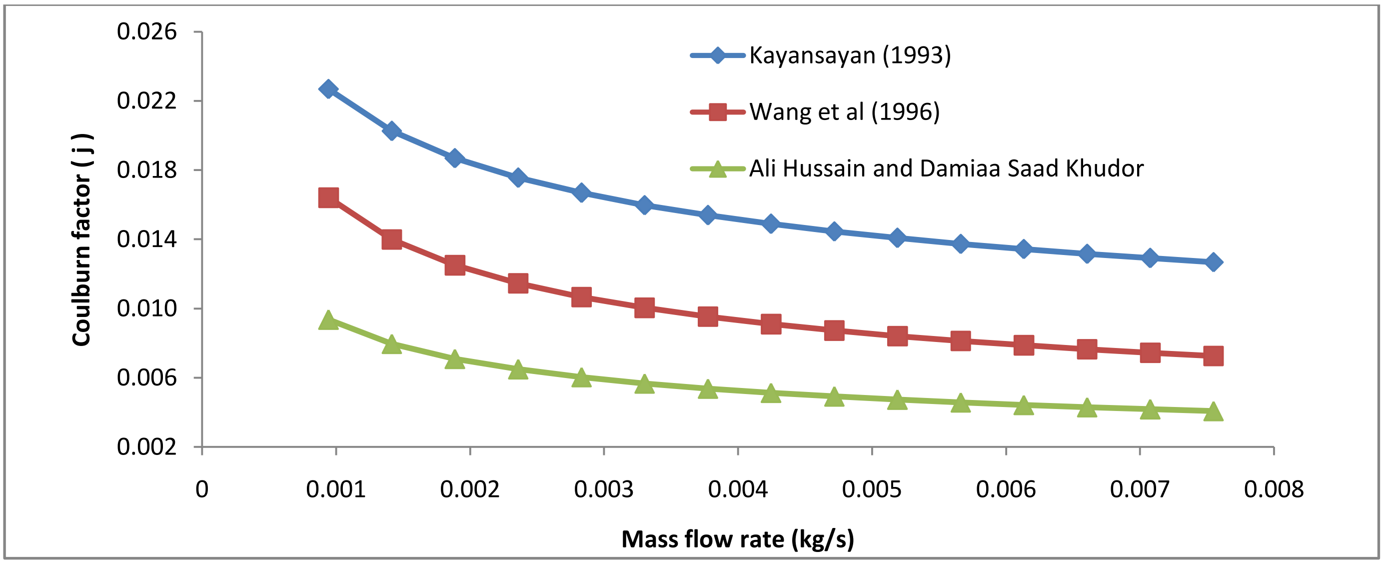

Figure 7 Effect of mass flow rate on Colburn (j) factor is shown in fig. for three different correlations.

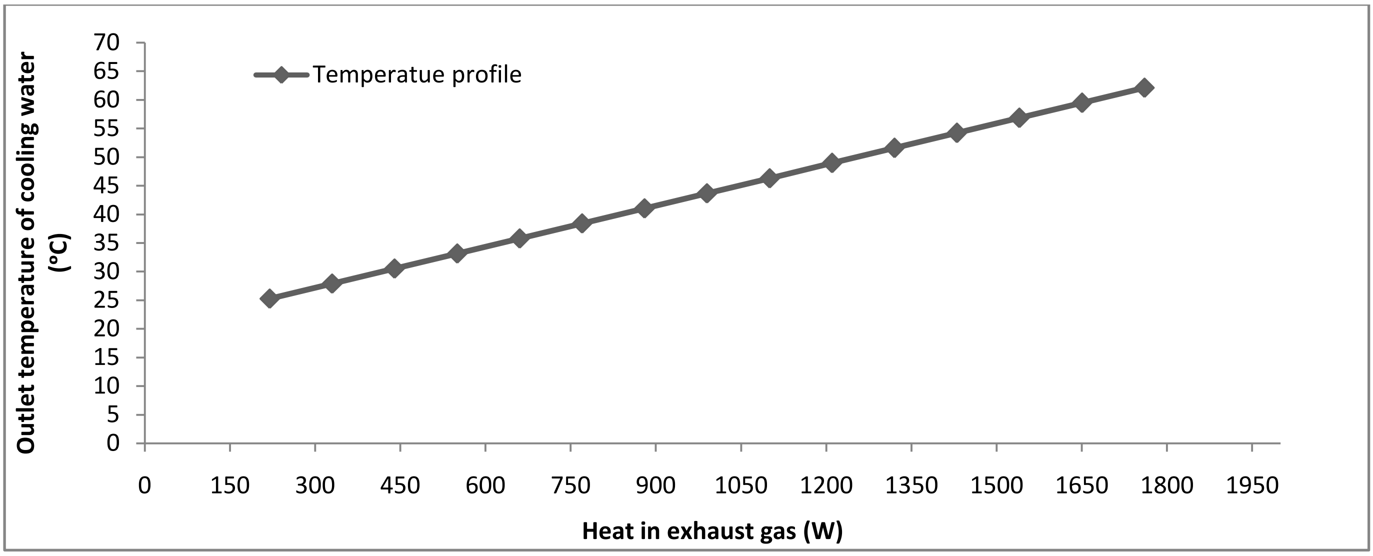

Figure 8 Variation in outlet temperature of cooling water by keeping the mass flow rate of cooling water constant.

IV. Conclusion

In this paper the effectiveness method is used to predict the overall thermal capacity of a fin and tube heat exchanger.

Load test on the engine was conducted to confirm the range of exhaust gas temperature at constant speed by S.S. Bhusnoor et al. (2016). It was found on the graph that as break power increases temperature of exhaust gas also increases.

In the present study, the effects of mass flow rate of exhaust gas on convective heat transfer coefficient are studied by using different theoretical correlations and plotted in graphs.

With the increase in Reynolds number the convective heat transfer coefficient increases.

With increase in Reynolds number Colburn factor (j) decreases.

References

[1] Wang C C and Chi K Y 2000 Heat transfer and friction characteristics of plain fin-and-tube heat exchangers part I: new experimental data. *Int. J. Heat Mass Transf.* 43: 2681–2691.

[2] W. Yaïci, M. Ghorab, E. Entchev, 3D CFD analysis of the effect of inlet air flow maldistribution on the fluid flow and heat transfer performances of plate-finand- tube laminar heat exchangers, Int. J. Heat Mass Transfer 74 (2014) 490–500.

[3] P.Pongsoi, S.Pikulkajorn, C-C Wang, S. Wongwises. Effect of number of tube rows on the air-side performance of crimped spiral fin-and-tube heat exchanger with a multipass parallel and counter cross-flow configuration, Int. J. Heat and Mass Transfer 55 (2012) 1403–1411.

[4] Jose Ferna´ndez-Seara, Francisco J. Uhıa, Jaime Sieres, Antonio Campo. A general review of the Wilson plot method and its modifications to determine convection coefficients in heat exchange devices. Applied Thermal Engineering 27 (2007) 2745–2757.

[5] Kayansayan N 1993 Heat transfer characterization of flat plain fins and round tube heat exchangers. *Exp.Therm. Fluid Sci.* 6: 263–272.

[6] D.G. Rich, The effect of fin spacing on the heat transfer and friction performance of multi-row smooth plate fin-and-tube heat exchangers, ASHRAE Trans. 79 (2) (1973) 135–145.

[7] Ali Hussain Tarrad, Damiaa Saad Khudor. Correlation for the Air-Side Heat Transfer Coefficient Assessment in Continuous Flat-Plate Finned Heat Exchangers.

[8] S.S. Bhusnoor, U.V.Bhandarkar, V. Sethi, P.P. Parikhb, Thermophoresis deposition studies for NaCl and diesel exhaust particulate matter under laminar flow, Journal of Aerosol Science 105 (2017) 84–93.

[9] Sadik Kakac, Hongtan Liu. Heat Exchanges Selection ,Rating and Thermal design. Second Edition

[10] McQuiston F C 1978b Correlation of heat, mass and momentum transport coefficient for plate-fin-tube heat trasnfer surfaces with staggered tubes. *ASHRAE Trans.* 84(1): 294–308.