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Thermal Analysis of Plate fin Heat exchanger in Aircraft Air-conditioning system

1. Dr.Srinivas Sharma Gangaraju, Associate professor, Mechanical Engineering Dept, MVSR Engineering College , Hyderabad, Telangana , India
2. Dr.Lakshmi Kameswari Gangaraju, Asst.Prof, Faculty of Mathematics, MVSR Engineering College, Hyderabad, Telangana , India.

Abstract

Plate fin heat exchangers are compact heat exchangers where beta factor (Surface Area to Volume) is less than 700 m^2 / m^3 and are exhaustively used in SOFC applications, aircraft air conditioning systems, MEMS and thermal management of electronic devices. In the present paper, a plate fin heat exchanger (PFHE) dimensions are specified and effectiveness of heat exchanger is arrived interms of NTU & C. The rating problem is solved and statistical correlations of exit temperature of hot fluid id expressed interms of pitch, length, thickness, specific heat , heat transfer coefficient , thermal conductivity and mass flux is estimated using linear regression model. The data model is developed using MS excel for above discussed variables. A case study of using PFHE for aircraft air-conditioning system is presented and discussed.

1 Introduction

The Heat exchange process occurs in a control volume , enclosed with adiabatic conditions , between two or more streams of fluid, of which one is hot and other is cold. Heat exchange occurs dynamically, between the hot and cold fluid stream, and achieving higher heat transfer rates within minimum volume is need of hour. Compactness of heat exchanger is defined as per beta factor (β) which is defined as the ratio of surface area to volume of the heat exchanger. As per the relation $\dot{Q}$=U*A*LMTD , it can be re-written in the form of $\frac{\dot{Q}}{LMTD} = U * \frac{A}{V} * V$, where surface area to Volume is beta factor (β) and hence rate of heat transfer per unit temperature drop is directly proportional to β and volume of fluid handled. If β is large then volume of fluid handled is reduced, which will largely reduce the weight of fluid. Such heat exchangers are used in situations where design criteria is minimization of weight, and will comply mostly to aerospace applications. Aircraft air-conditioning systems handle R-729 as refrigerant, which is nontoxic, non-flammable, cheaply and abundantly available, where air from atmospheric conditions is taken through the inlet diffuser (assuming no shock at inlet conditions) and rammed to required pressure, without doing any work on the system. This air is then passed into main compressor, which is axial flow , compresses the air from the ram air pressure to the combustor designated pressure. This is generally 40~50 bar for producing the necessary thrust in the exhaust section of gas turbine cycle. For cooling purpose the compressed air is bled at 5 bar from the main compressor and passed through the air-to-air heat exchanger, where high pressure, high temperature, compressed air is cooled by ram air taken from the outside conditions. This heat exchanger cools the high pressure air , to high pressure low temperature air ,with a pressure drop of less than 8%. This air is then sent into a expander, which is generally centrifugal turbo machine, which expands to cabin pressure (which is maintained higher than ambient air at higher altitudes). During expansion the air attains lower temperature than ambient, and it is used for cabin cooling. The heat exchanger is generally crossflow type of heat exchanger, in which hot and cold streams move at right angles to each other. The disadvantage of crossflow heat exchangers is that uniform temperature at heat exchanger outlet is very difficult, unless and until mixing mechanism is provided. So , plate fin heat exchangers with offset are most suited for such applications, which satisfy the requirement of β factor less than 700 m^2/m^3, which is generally classified as compact heat exchangers. The operation and working is indicated in the figure1. The air expanded in the cooling turbine produces work, which is pumped to a axial flow fan, which draws the ram air from ambient into the heat exchanger. The blue colored dotted line indicates the flow of primary air from diffuser outlet, which is called rammed air. The red colored dotted line indicates the secondary air bled from the main compressor of aircraft power plant. This air is at high pressure and high temperature, than the primary air, available at the inlet of the compressor. Modifications to the simple cooling cycle were implemented such as placing a liquid nitrogen bath after the air to air heat exchanger , which will further lower the temperature of air entering the cooling turbine. This is called simple evaporative cycle, whose COP is higher than simple cooling cycle. Higher TR requirement cabin cooling systems have employed boot strap air conditioning system in which air is compressed after evaporative cooling in secondary compressor and then expanded in the cooling turbine. This is observed to be most efficient cooling system, which is employed in large capacity TR requirement aircrafts. The present paper is focused on the thermal systems design of heat exchanger, in which both streams are air with different thermal gradients and pressure gradients. As the heat exchanger is an integral part of aircraft dead load, which have to be lifted by the lift component of propulsion power, minimization of weight is a primary concern. The heat exchanger for aircraft Air- conditioning is proposed to be a cross flow, mixed type of heat exchanger, with extended surface area to enhance heat transfer between the both streams of air. The Plate fin Heat exchanger (PFHE) qualifies all the requirements of air-to-air heat exchanger used in the aircraft Air conditioning system, in which β factor is less than 700 m^2/m^3. The cycle of operation on temperature-entropy diagram is indicated in fig.2 , where 0-1 indicates the ram compression, process 1-2 compression is compression in the main compressor, process 2-3 heat loss in PFHE, process 3-4 represents the expansion in cooling turbine and finally the process 4-5 indicates the heat gain by refrigerant in cabin or otherwise refrigeration effect in the cabin.

$$COP = \frac{Refrigeration\ effect}{Work\ done\ on\ the\ system} = \frac{(T5-T4)}{(T2-T1)} \text{ ----------------------(1.1)}$$

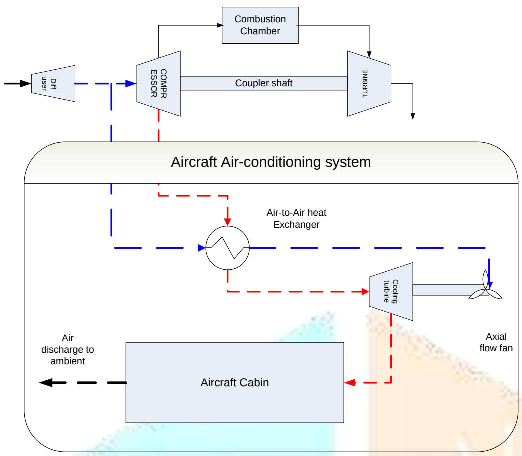


Figure 1: Simple Cooling system

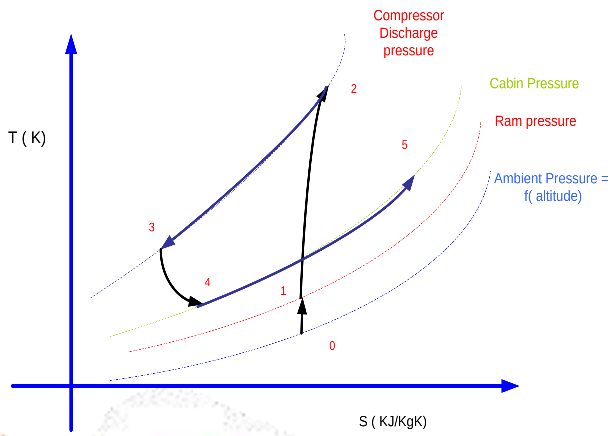


Figure 2: T-S diagram indicating the simple cooling cycle

The COP of the simple air-conditioning cycle is given by relation 1.1, in which lower the value of T_4, higher will be the COP of the system for the given aircraft load configuration, without altering the other dependent parameters such as pressure ratio, work input to the compressor and ambient conditions. Lower value of T_4 (Cooling Turbine outlet temperature) is possible if the value of PFHE outlet temperature is lower. Hence PFHE is playing a vital role in arriving at the COP of aircraft air-conditioning system. In the next section PFHE and its system design is discussed in detail. M. Picon-Nuñez et al [2] had presented the methodology for the design of compact plate–fin heat exchangers with full pressure drop utilization . He had developed volume performance index as per the pressure drop, heat transfer coefficient and heat exchanger volume. The authors have presented , an thermal and hydraulic design for PFHE. L.sheik Ismail et al [3] have developed thermo-hydraulic design of compact heat exchangers with zero dimension analysis and insisted that calburn and fanning factor affects the heat exchanger performance. Three offset strip fin and 16 wavy fin geometries used in the compact plate-fin heat exchangers have also been analyzed numerically. Multiobjective optimization algorithm based on randomly generated population is also sued by various researchers to arrive at minimization of total weight. Hao Peng et al [4] had minimized the weight and cost function using MOGA and neural networks with back propagation algorithm (Hybrid Genetic Algorithm) , in which the population is randomly generated and total length and width of PFHE core, number of hot side layers, fin height and pitch on each side of PFHE are considered as variables to be optimized by means of GA combined with BP method. This optimization method of PFHE is universal and can be used for various PFHEs. Sepehr Sanaye et al [5] have optimized the PFHE using effectiveness-NTU method, in which the heat exchanger pressure drop and effectiveness are estimated. Fin pitch, fin height, fin offset length, cold stream flow length, no-flow length and hot stream flow length were considered as six design parameters and pareto optimal solution set are obtained using the genetic algorithm. Manglik et al [6] , have developed the respective asymptotes for fanning factor f and calburn factor j , which are correlated by power law expressions in terms of Re and the dimensionless geometric parameters α, δ, and γ. Finally, rational design equations for f and j are presented in the form of single continuous expressions covering the laminar, transition, and turbulent flow regimes. S.J. Wright et al [7] have described the aircraft's air-conditioning system functions and the use of external air flow from outside to act as a cooling source. B.B. kuchhadiya et al [8], created an experimental set up has been built in the laboratory to test the Plate fin Heat exchanger. Sets of experiments had conducted to determine the thermal performance of the given heat exchanger. Mass flow rate of cold fluid, mass flow rate of hot fluid, hot fluid inlet temperature, cold fluid inlet temperature, hot fluid and cold fluid inlet pressure are considered as input parameters. The values of the heat transfer co-efficient, effectiveness and pressure drops are obtained for the different value of the input parameters. In the present paper Plate fin Heat exchanger with straight rectangular offset strips are considered for aircraft air-conditioning system. The stagnation temperature at the inlet of the compressor is dependent on the Mach Number of the flight , which is again a function of altitude of the flight. The pressure and temperature at inlet of the diffuser were determined using the pressure altitude relations, temperature-altitude relations with isentropic relations pertaining to stagnation state.

2 Thermal modeling of PFHE

In the process of thermal modeling of heat exchangers, whether it is a Rating duty problem or sizing problem, the problem specifications are input parameters for the design process. For rating duty problem, size of heat exchanger is specified and energy rating is arrived, whereas in sizing problem energy duty or rating is specified such as 100 Kw_{th} or so and size of heat exchanger (dimensions) are arrived. Thermo-physical properties and operating characteristics are arrived from material selection and thermo-physical properties of fluids. In the present work rectangular offset straight Plate fin heat exchanger is elaborated, with respect to thermal and hydraulic design. ε- NTU Method is adopted to determine the effectiveness of the PFHE interms of Number of transfer units (NTU) and Heat capacity ratio (CR). Franco et al have given relation for "ε" interms of modified Bessel function of NTU and CR, which is given by eq.2.

$$\varepsilon = (1 - e^{1(1+CR)*NTU})*[I_0\ (2NTU\sqrt{CR}) + \sqrt{CR} * I_1\ (2NTU\sqrt{CR}) - \frac{1-CR}{CR}\sum_{n=2}^{\infty} CR^{\frac{n}{2}} I_{1\,n}\,(2NTU\sqrt{CR}\ ]$$

---eq(2)

The overall heat transfer coefficient is obtained by reciprocal of total thermal resistance offered by the PFHE. The rectangular PFHE geometry is indicated in figure 3.

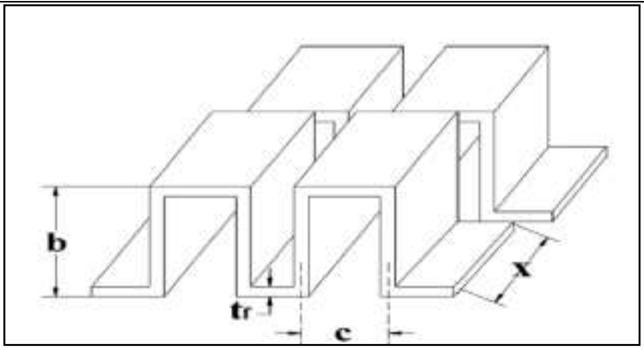


Figure 3: Geometry of PFHE

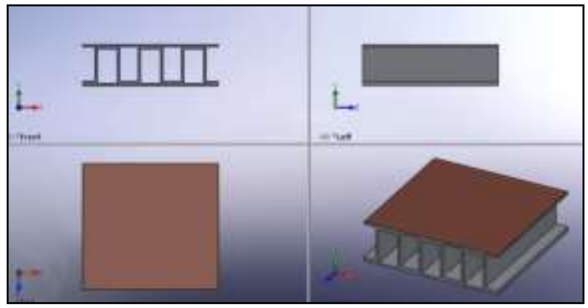


Figure 4: Views of PFHE on Hot side (array)

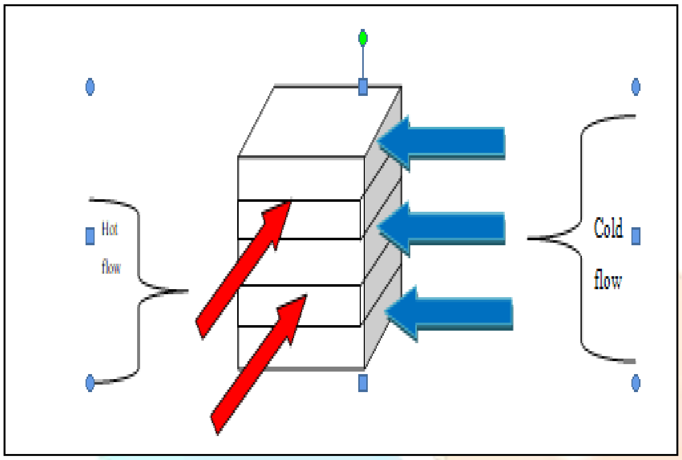


Figure 5: stack view of PFHE

The total surface area of the PFHE is given by eq(3). Where β is defined as the ratio of Area of cell to Volume of cell $\beta = A_{cell} / V_{cell}$. Where 'b' is height of fin , 'c' is pitch , t_f is thickness of fin and 'x' is the length of the plate.

$$A_{total} = (\beta V_p)_c + (\beta V_p)_h \qquad \text{eq(3)}$$

$$\beta = \frac{2(b-t_f)X + 2(c-t_f)X + 2(b-t_f)t_f + Ct_f}{bcX} \qquad \text{eq(4)}$$

Volume between plates of hot and cold plates of heat exchanger $V_{p,c}$ & $V_{p,h}$ are given by eq.5 and eq.6, in which N_p are assumed for hotside and N_p +1 passages for cold side.

$$V_{p,c} = L_c L_h b_c (N_p+1) \qquad \text{eq(5)}$$

$$V_{p,h} = L_c L_h b_h N_p \qquad \text{eq(6)}$$

Number of passages is given by $N_p = \frac{Ln - bc\_2tw}{bh+bc+2tw}$, where t_w is the plate thickness, L_c, L_h and L_n are cold stream length, hot stream length and non flow length respectively. The fin surface efficiency is given by eq.7, in which A_f is single fin surface area enhancing heat transfer.

$$\eta_s = 1- \frac{A_f}{A_{cell}} (1 - \eta_f) \qquad \text{eq(7)}$$

Where η_f is the efficiency of fin which is equal to Tanh(mL)/mL (Note : mL is fin factor)/ The calburn factor 'j' is given by eq.8 ,

$$j= 0.6522(Re)^{-0.5403} (\alpha)^{-0.1541} (\delta)^{0.1499}(\gamma)^{-0.0678} x[1+5.269x10^{-5} (Re)^{1.34} (\alpha)^{0.504} (\delta)^{0.456}(\gamma)^{-1.055}]^{0.1} \qquad \text{eq(8)}$$

The friction factor 'f' is given by the relation eq.9, which is related to calburn analogy.

$$f=9.6423(Re)^{-0.7422} (\alpha)^{-0.1856} (\delta)^{0.3053}(\gamma)^{-0.2659} x[1+7.669x10^{-8} (Re)^{4.429} (\alpha)^{0.920}(\delta)^{3.767}(\gamma)^{0.236}]^{0.1} \qquad \text{eq(9)}$$

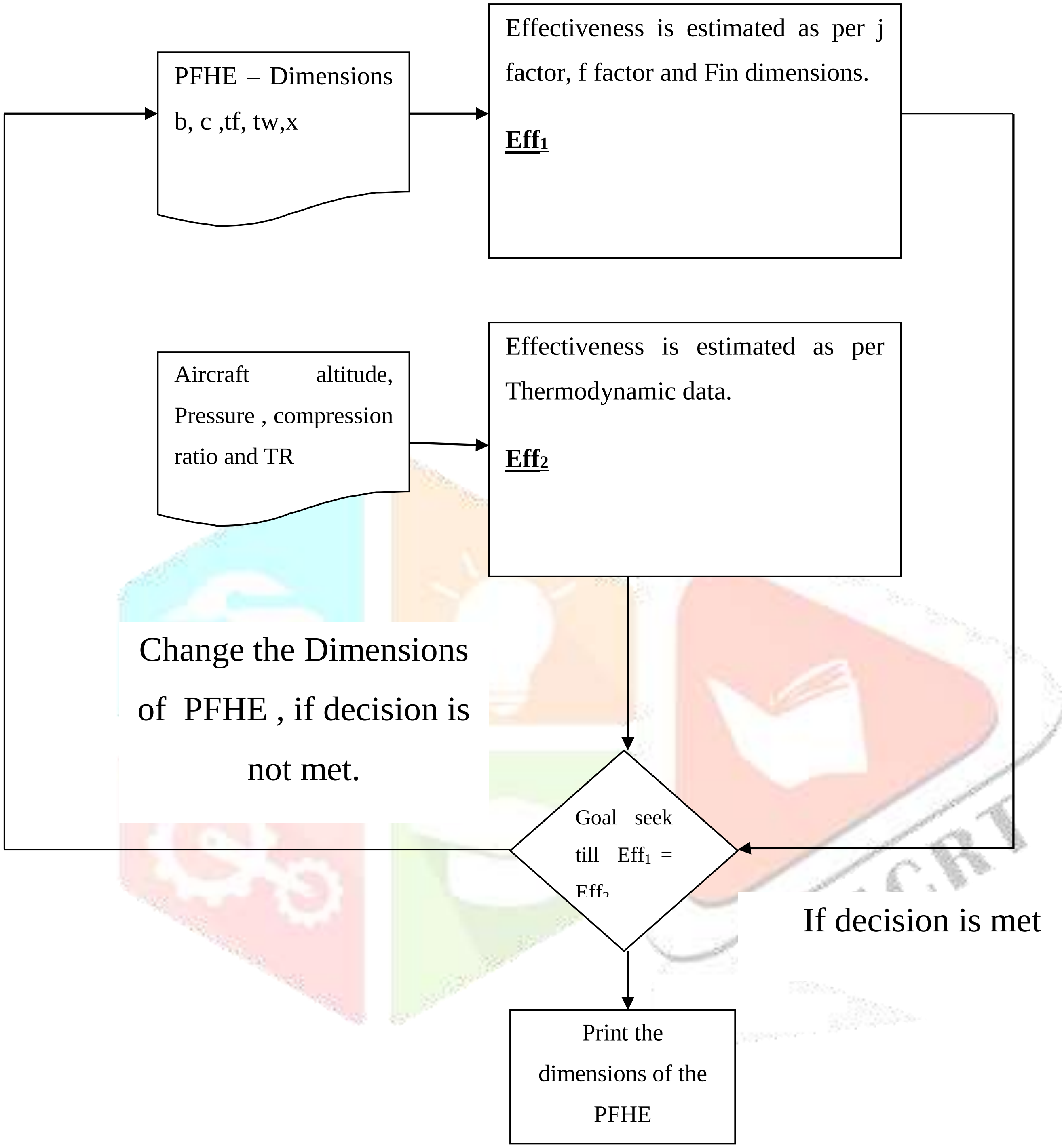
These relations are valid for $120 < Re < 10^4$, $0.134<\alpha<0.997$, $0.012<\delta<0.048$ and $0.041 <\gamma< 0.121$, where $\alpha = c/b$, $\delta= t_f/x$, $\gamma= t_f/c$; Stanton number (St) is computed from calburn factor given by $St= j/ Pr^{2/3}$, where Pr is prandtl number. The heat transfer coefficient 'h' is given by $h= St.G.C_p$, where G is mass flux determined by hydraulic diameter and C_p is specific heat. The pressure drop characteristics are given by the eq.10, in which v_{ave} is the average velocity and v_{in} is the velocity at inlet of heat exchanger.

$$\Delta P = G^2 (v_{in} /2)[(1+\sigma^2)(v_{out}/v_{in} -1)+f(A_{total}/A_{flow})(v_{ave}/v_{in})] \qquad \text{eq(10)}$$

$$COP)_{simple\ cycle} = (T_5 - T_4)/(T_2 - T_1) \qquad \text{eq(11)}$$

3 Data model in MSExcel

MS Excel 2003 version is used in the present work and calculations were performed and effectiveness is arrived from the PFHE data and again it is obtained from stand point of aircraft operation. Goal seek function is used to arrive at the optimum dimensions of PFHE , matching the operation of aircraft. The matching procedure is indicated in the flowchart shown below.


PFHE – Dimensions b, c ,tf, tw,x
Effectiveness is estimated as per j factor, f factor and Fin dimensions.
Eff1
Aircraft altitude, Pressure , compression ratio and TR
Effectiveness is estimated as per Thermodynamic data.
Eff2
Change the Dimensions of PFHE , if decision is not met.
Goal seek till Eff1 = Eff2
If decision is met
Print the dimensions of the PFHE

4 Results & Discussions

The effectiveness of Heat exchanger is plotted for all variables of PFHE , With increase in Fin height, the effectiveness is decreased from 0.55 to 0.1. With increase in length of the PFHE from 5 cm to 30 cm , the effectiveness is decreased. This is indicated in Fig.6 and variation with pitch is indicated in Fig.7.

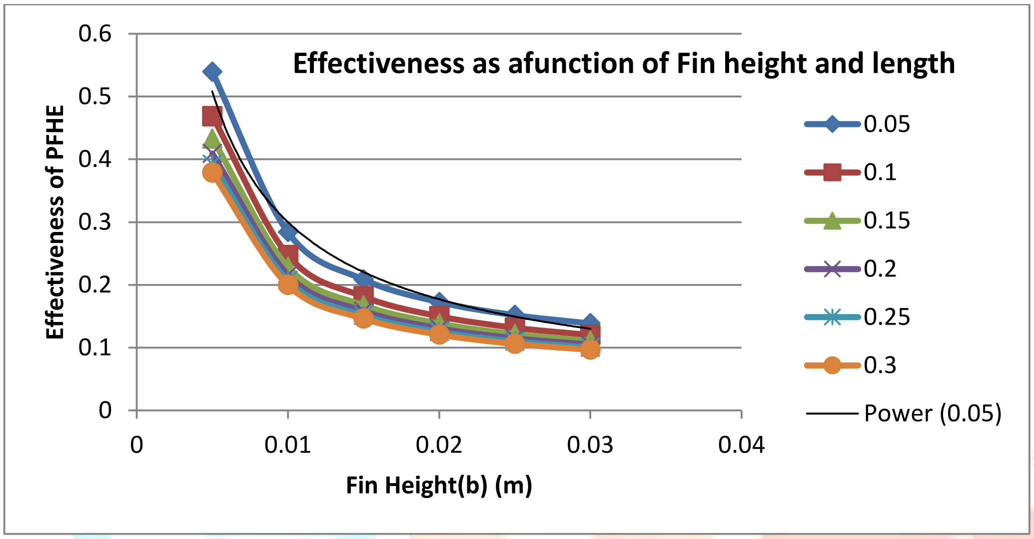


Figure 6: Effectiveness as a function of Fin height & length

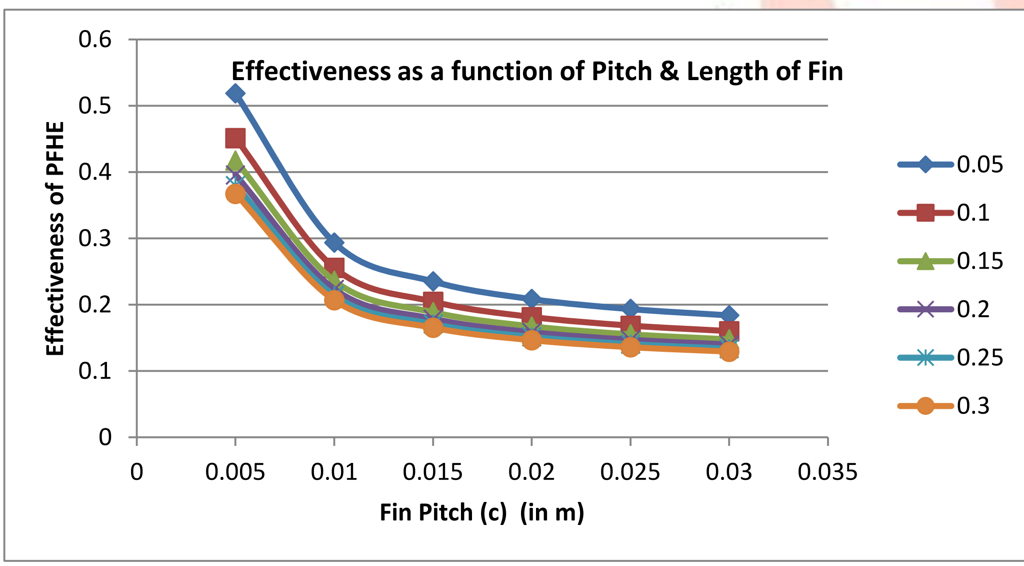


Figure 7: effectiveness as a function of Pitch and length of Fin

Fig.8 indicates the variation of effectiveness with length of hot and cold flow sides, and for a square of 0.4 m x 0.4 m , the effectiveness is almost 0.2.

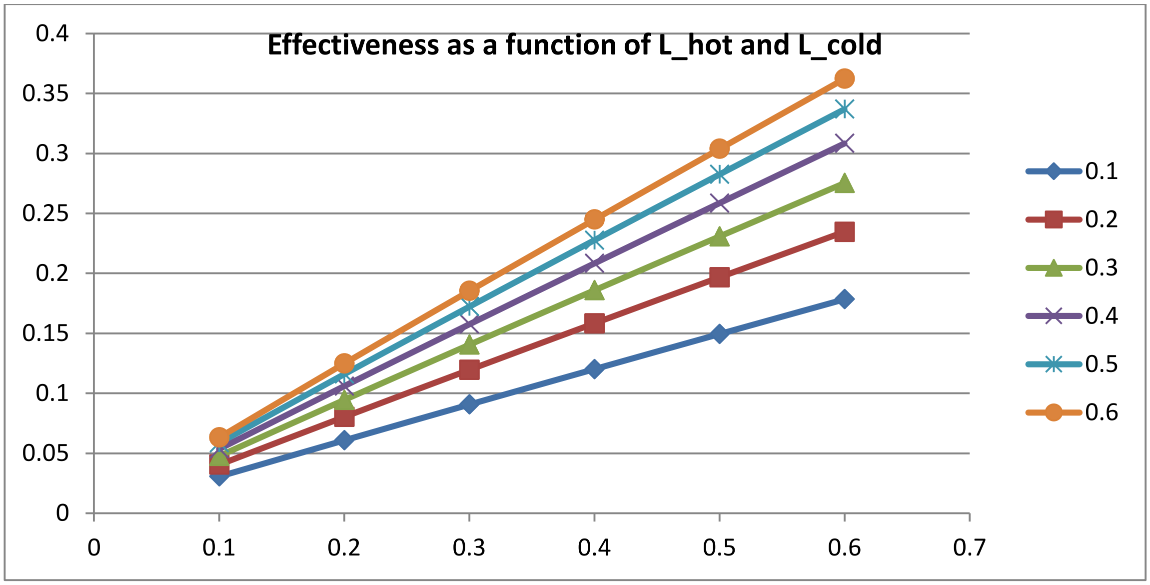


Figure 8: Effectiveness as a function of length of hot and cold flow sides

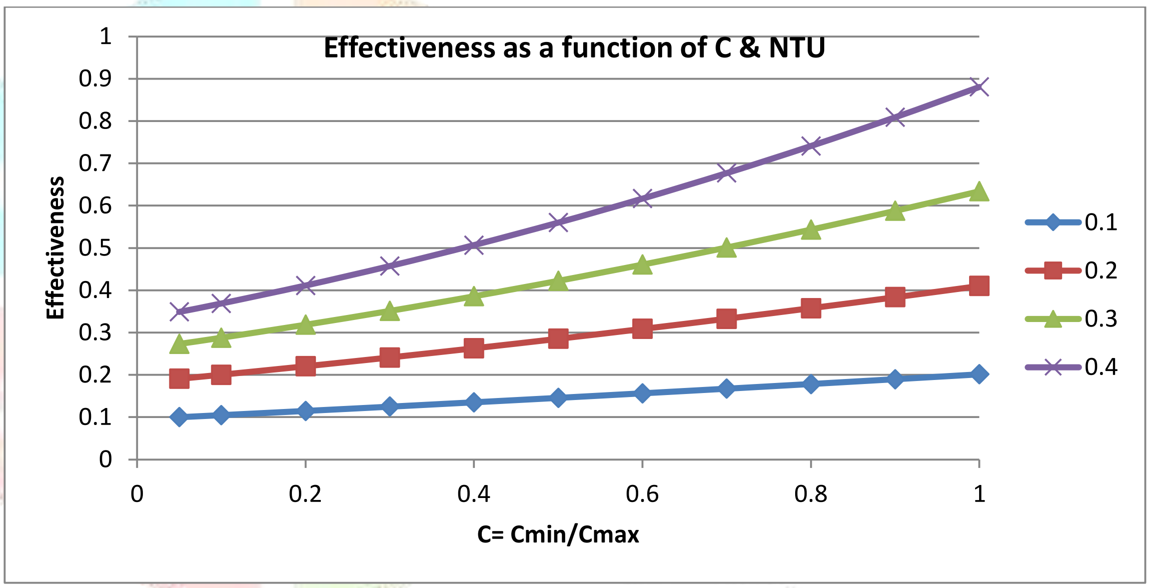


Figure 9: Effectiveness as a function of CR & NTU

With increase in NTU and C (Heat capacity Ratio)m the effectiveness is increased and can be attained a value of 0.9. This variation is indicated in Fig.9. The Value of Cr =0 is omitted as there is no possibility of phase change when dealing with air(as long as operating pressure is no below its saturation pressure). The other important variable affecting the performance of PFHE is number of passages and β factor. The β factor for compact heat exchanger lies between 200 ~ 700 m^2 / m^3. The variation of effectiveness with β and N_p is indicated in fig.10.

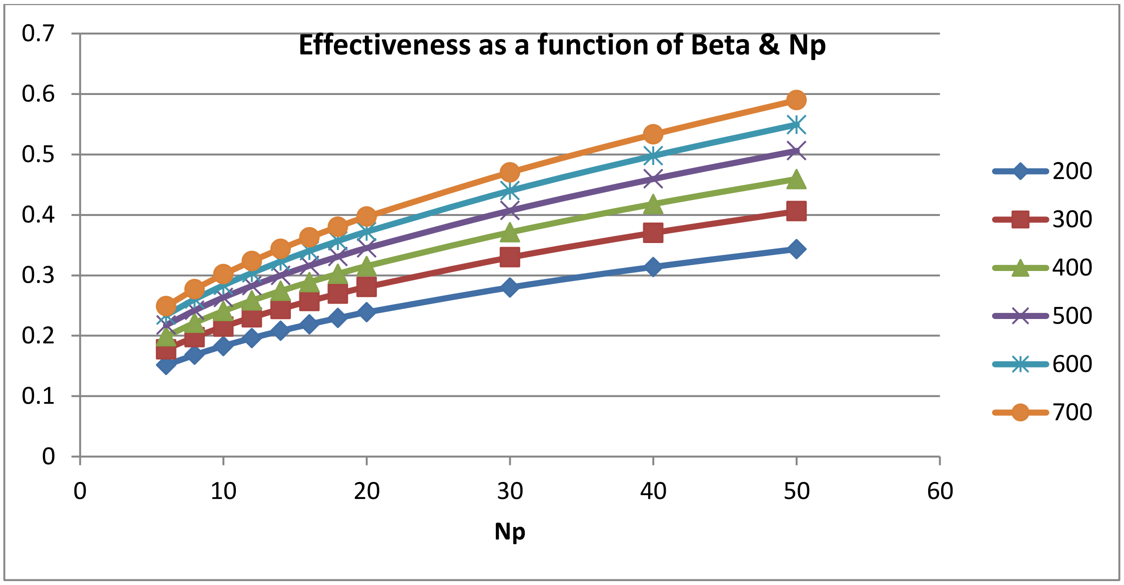


Figure 10: Effectiveness as a function of Np & Beta factor

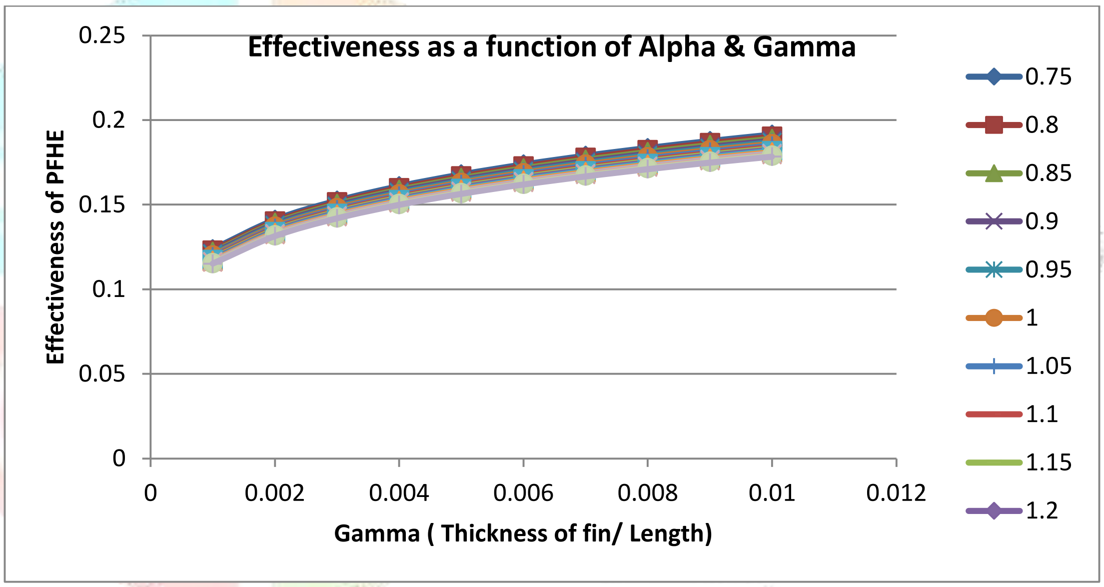


Figure 11: Effectiveness as a function of Alpha & Gamma Factor

The α factor & γ factor determine the dimensions of the PFHE in non dimensional form. This non-dimensional form interms of α factor is ratio of pitch to height of fin and γ factor is thickness of fin to pitch provide the dimensional sizing of PFHE. This plot is extremely useful for sizing problems, when b,c,tw,tf and x are given to determine the rating of Heat exchanger.

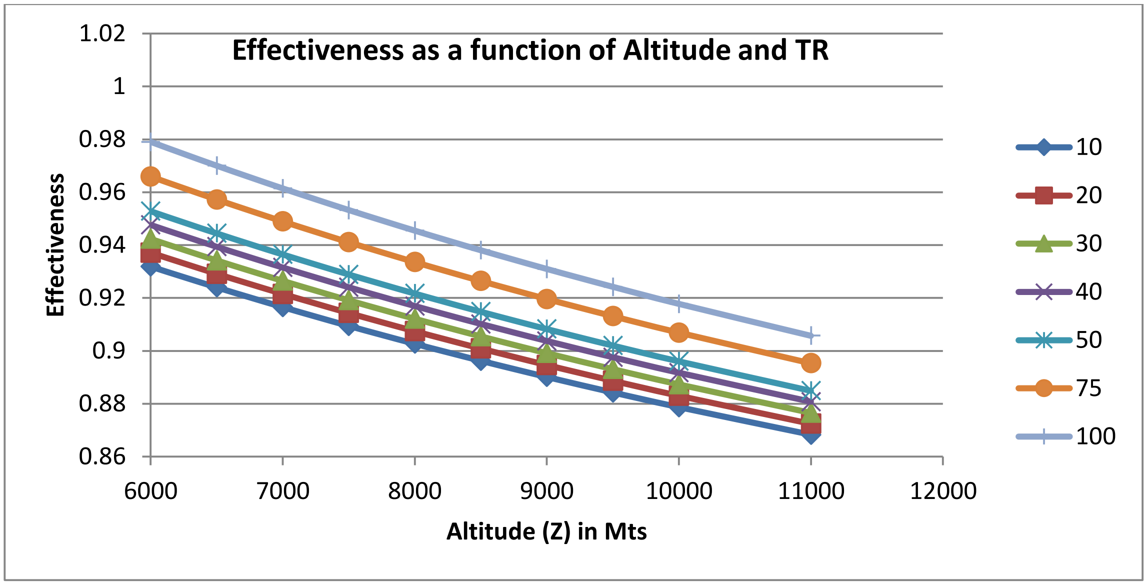


Figure 12: Effectiveness as a function of altitude (Z) and required TR

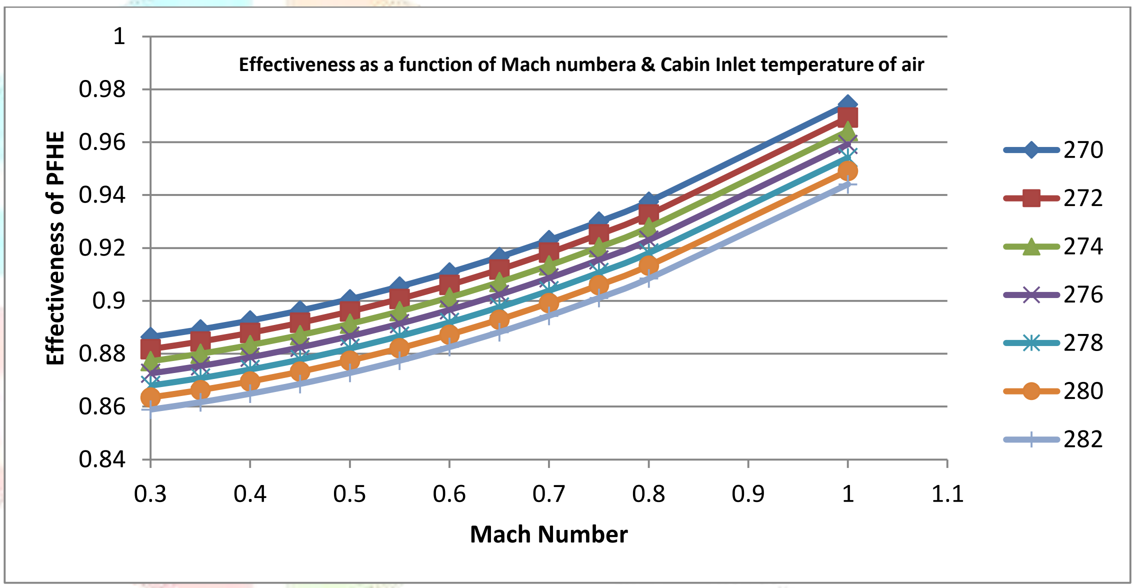


Figure 13: Effectiveness as a function of Mach No & Cabin air inlet temp

It was observed that at higher Mach number reaching sonic conditions, the effectiveness of heat exchanger has increased and at sonic conditions the effectiveness is almost 0.95. linear Regression model iwas used to develop a statistical correlation of effectiveness of PFHE interms of the Altitude, Mach No, Pressure ratio of gas Turbine and Ton of refrigeration .

Regression Statistics	
Multiple R	0.999999816
R Square	0.999999631
Adjusted R Square	0.937499562
Standard Error	0.000615163
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	16.42399768	4.10599942	10850209.05	2.94352E-48
Residual	16	6.05481E-06	3.78426E-07		
Total	20	16.42400373			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Altitude	0.000903624	1.81169E-06	498.7735597	5.74636E-35	0.000899784	0.000907465	0.000899784	0.000907465
Mach	0.153117896	0.006998881	21.87748249	2.38887E-13	0.138280932	0.167954861	0.138280932	0.167954861
P_ratio	0.001230499	0.000279722	4.398998911	0.000448172	0.000637514	0.001823484	0.000637514	0.001823484
TR	-0.091851738	0.000165123	-556.2623574	1.00326E-35	-0.092201783	-0.091501693	-0.092201783	-0.091501693

The estimated correlation is $\varepsilon = 0.000903624 * Z + 0.153117896 * M + 0.001230499 * PR - 0.091851738 * TR$

where Z is altitude in mts, M is Mach number , Pr is pressure ratio and TR is tons of refrigeration and ε is effectiveness of Heat exchanger.

5 Conclusions

The plate fin Heat exchanger is designed for optimum effectiveness of 0.9 and flowing dimensions were arrived using goal seek optimization in MSEXCEL. The dimensions are indicated below

Fin geometry	(in SI Units)	Fluid properties	(in SI Units)
Length (x)	0.2	Cp	1005
Height(b)	0.01	k	0.025
Pitch(c)	0.01	M_cold	1
L_hot(lh)	0.613756425	Cp_cold	1005
L_cold(lc)	0.25	Cmin	1005
L_nonflow	0.3	Cmax	10050
thickness(tf)	0.001	C	0.1
thickness(tw)	0.01		
M_hot	10		
Mu_hot	2.00E-05		

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