ANALYSIS OF ENGINE OIL COOLER OF AN UNMANNED AERO-ENGINE AT VARIOUS ALTITUDES

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ABSTRACT

The present analysis is essentially a theoretical approach to establish the performance characteristics of engine oil cross flow heat exchanger with cold air as the unmixed coolant at different altitudes of the flight. The present configuration of the heat exchanger is a specific case being used by Vehicle Research Development Establishment (VRDE). The study takes into account the thermo- physical property variation of engine oil with respect to temperature in the oil ducts. The predictions from theoretical considerations are compared with the conventional empirical equations available in heat transfer handbooks. It is observed that the theoretical results related to effectiveness of heat exchanger deviate markedly from results of computational procedures found in the heat transfer data books. Further, the present analytical approach is rendered into a dimensionless correlation .The outlet temperature estimates from the analytical study for the engine oil and cold air at different altitudes agree very satisfactorily with the corresponding values from the proposed correlation equation.

Key words: Mixed cross flow heat exchanger, property variation, altitude effects on effectiveness

INTRODUCTION

Conventional design of several types of heat exchangers is well standardized and established. The procedures are mostly available in handbooks of heat transfer [1-7]. However, these design procedures might deviate if specific constructional features or thermal conditions of the media deviate from the established norms and standards. The overall heat transfer coefficient is the essential parameter in the evaluation of area requirement separating both the hot and cold media. These values in turn determine the number of transfer units. The thermal resistances on the hot and cold surfaces depend on the thermo-physical properties of the thermally interacting hot and cold media. In the heat exchanger under consideration, the thermo-physical property variations of the engine oil are found to be dependent on the bulk temperature of oil. In contrast, the properties of coolant air strongly vary with the altitude of the flight unlike in the case of a stationery heat exchanger on the test bed. Thus, special considerations in the design are to be taken care to accomplish targeted performance and effectiveness at different air velocities and altitudes of the plane. The present study is related to a specific heat exchanger employed in unmanned aircraft of VRDE. The task is the one related to the reengineering technology of an already working model of a heat exchanger shown in Plate 1.

For a cross flow heat exchanger with both streams unmixed, the effectiveness, ε can be predicted from the following available empirical equation (1) available in the literature [4]

$$\varepsilon_1 = 1 - \exp\left[\frac{\exp(-C\ NTU)^{0.78} - 1}{C\,(NTU)^{-0.22}}\right] \qquad (1)$$

where the Number of Transfer Units is defined as,

$$\text{NTU}=\left[\frac{UA}{C_{\min}}\right] \qquad (2)$$

$$C = \frac{C_{\min}}{C_{\max}} \qquad (3)$$

$C_{\min}$ is the minimum of $C_h\,\dot{m}_h\ :C_c\,m_c$ & $C_{\max}$ is maximum of $C_h\,\dot{m}_h\ :C_c\,m_c$

In the conventional design of cross flow heat exchangers available in the hand books the surface area 'A' for both hot and cold fluids is more or less the same. In a previous attempt [9], the authors investigated the case of a stationery radiator and the effectiveness parameters are obtained as functions of system variables. It is found that by varying the fin effectiveness ratio, the predictions from the model agree reasonably with the results from Equation 1of the hand book . However, the present study is mainly devoted to the case of an unmixed heat exchanger for cooling the engine oil flowing at high values ranging from 90 – 140 ^{0}C at different altitudes of the flight of an aero-engine.

Description of the oil cooled heat exchangers

The heat exchanger to be analyzed is an air cooled compact heat exchanger of cross flow type with triangular plate fins on air side ducts sandwiched between narrow rectangular passages of hot engine oil. The ambient air is made to flow at right angles to flow of the engine oil as can be seen from Fig. 1. The dimensions of the heat exchanger under study are as follows:

Particulars of hot fluid channels

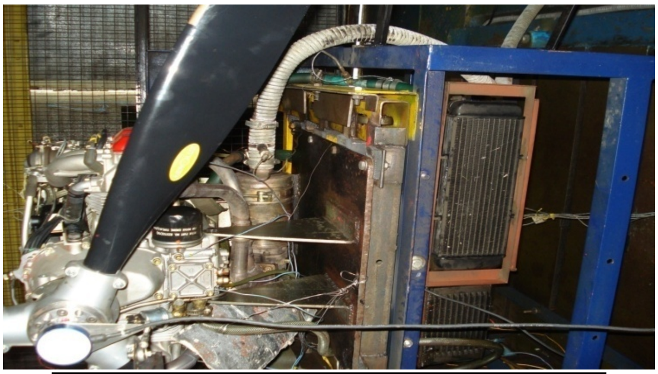
Number of engine oil channels=10

Equivalent diameter of rectangular channel $\frac{4A_h}{P_h} = D_h = 4.7mm$

Length of the channel from header to header=180mm

$\frac{L_h}{D_h} = 180/4.7 = 38.3$

Total surface area of the engine oil ducts=0.15 m^2



View of the Engine Oil Heat Exchanger

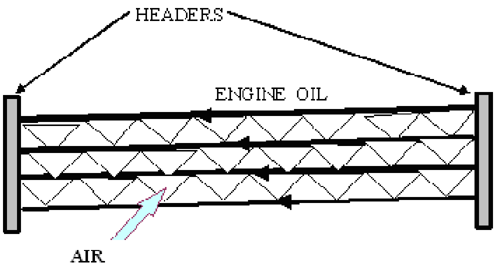
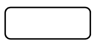


Fig 1. SCHEMATIC OF CROSS FLOW UNMIXED ENGINE OIL HEAT EXCHANGER

Dimensions of Tube and Fin triangle

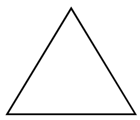
Cross section of tube (for flow of hot fluid)



Height of tube = 2.5 mm
Width of tube = 40 mm
Length of tube = 180 mm

Number of tubes = 10

Fin triangle formed by two fins on tube surface (for flow of cold fluid)



Height of triangle) = 8.5 mm
Base of triangle) = 3 mm
Thickness of fin = 0.5 mm
Side of triangle = 8.63 mm

Number of fins in a row = 72
Number of fin rows = 12

Dimensions of Tube and Fin triangle in the oil

Particulars of air ducts

Total number of air ducts in all rows=780

Equivalent diameter of triangular duct $\frac{4A_c}{P_c} = D_c = 2mm$

Length of the duct=40mm

$\frac{L_c}{D_c} = 19.04$ Total surface area of the oil ducts=0.68m^2

Properties of Engine oil

The properties of SAE 20W 40 oil are taken from the available data books and subjected to regression analysis. The regression analysis gives correlations for various properties as a function of temperature for the varying temperature between the limits 90 to 140 ^{o}C.

Density, ρ =899.75-0.595[T] [kg/m^3]

k=0.1473-1.18e-4[T] + 1.309e-7*(T^2) [w/m k]

C$_p$=1798.03+4.076[(T] +1.309e-3*[T^2] [j/kg k]

μ=0.6022-0.01755[T] +1.993e-4[(T^2]-1.0198e-6[T^3] +1.96e-9[T^4] [kg/m-s]

Table 1. Property variation of Engine oil

T ^{0}C	ρ [kg/m^3]	k [w/m k]	C_p [j/kg k]	ν (m^2/s)	μ [kg/m-s]
40	876	0.1422	1964	2.41E-04	0.2111
60	864	0.1407	2047	8.30E-05	0.0717
80	852	0.1384	2131	3.70E-05	0.0315
100	840	0.1372	2219	2.00E-05	0.0168
120	828	0.1349	2307	1.20E-05	9.94E-03
140	816	0.1338	2395	8.00E-06	6.53E-03
160	805	0.1314	2483	5.00E-06	4.03E-03

Properties of air with altitude:

Source of information:

Density, Specific heat, thermal conductivity and viscosity shown in table 1. are taken from the website named "www.aerospaceweb.org"

Table 2. Property variation of air at different altitudes

Height ft	Density kg/m^3	Viscosity kg/m-s X10^5	Kinetic Temp ^{o}C	Thermal Conductivity X10^2
0	1.225	1.7894	15	2.5326
500	1.207	1.7846	14	2.5248
1000	1.189	1.7798	13	2.5170
2000	1.154	1.7702	11	2.5014
5000	1.055	1.7412	5.1	2.4544
10000	0.904	1.6922	-4.8	2.3754
15000	0.771	1.6424	-14.7	2.2957
20000	0.653	1.5917	-24.6	2.2153
25000	0.549	1.5401	-34.47	2.1341
30000	0.459	1.4876	-44.35	2.0522

X = Height / 10000

Density (kg/cu.m) = $1.224 – 0.3494\ X + 0.03164\ X^2$

Viscosity (kg/m-s) = 10^{-5} $(1.789 – 0.0954\ X – 0.00173\ X^2$

Kinetic Temperature (^{o}C) = $14.99 – 19.8\ X + 0.008\ X^2$

Pressure (milli bar) = $1.011 – 0.3502\ X + 0.03814\ X^2$

Thermal conductivity (W/m-K) = 10^{-2} $(2.533 – 0.1557\ X – 0.001474\ X^2)$

Cp = 1007 J/kg-K
k = 0.0263 W/m-K

FORMULATION

The following assumptions are made in the formulation of the problem

1. The wall of the tubes dissipates heat to the triangular fin geometry under constant wall temperature conditions.
2. The mean operating temperature of the air ducts will be slightly at different temperature dependent on fin efficiency η_f of the walls. However, η_f in the analysis is taken as unity.
3. The thermo physical properties of hot fluid i.e. engine oil are dependent on local bulk temperature .
   For the temperature range 60-160 ^{0}C the following relationships hold good for the data of engine oil taken from [5]
   Density=899.75-0.595[T] [kg/m^3]
   k=0.1473-1.18e-4[T] + 1.309e-7*(T2) [w/m K]
   Cp=1798.03+4.076[(T] +1.309e-3*[T2] [j/kg K]
   □=0.6022-0.01755[T] +1.993e-4[(T2]-1.0198e-6[T3] +1.96e-9[T4] [kg/m-s]
   These relationships are employed in the thermal modeling of the cross flow unmixed heat exchanger.
   The local heat transfer for the hot fluid channel can be estimated from the relations:
   $Nu_h=1.9656\ Gz_h^{0.333}$: $Nu_C=1.9656\ Gz_C^{0.333}$ where Gz_h and Gz_C are estimated as local magnitudes.
4. The flow of the hot and cold fluid correspond to laminar regime i.e. Re_c and Re_h <2300.Hence, the analysis is confined to these practical ranges of Reynolds number of the heat exchanger under consideration.
   With in the framework of these assumptions, the enthalpy variation of the medium in the hot channel can be written by the energy equation as follows:

Hot Fluid

The variation of mean bulk temperature T_h of hot fluid at any location in the hot fluid channel

$$-\frac{dT_h}{(T_h - T_W)} = \left[\frac{h_h\ \pi D_h}{\dot{m}_h C_h}\right] dz = \frac{4Nu_h(Z)}{Gz_h(Z)} d\left[\frac{z}{L_h}\right] \quad \text{where}\ T_{h2} < T_h < T_{h1} \qquad (4)$$

Where

$$Nu_h(z) = 1.86\left[\mathrm{Re}_h\,\mathrm{Pr}_h\,\frac{D_h}{L_h}\right]^{0.333}$$

Further, $$\frac{Nu(Z)}{Gz(Z)} = 4x1.86\left[\mathrm{Re}_h(z)\,\mathrm{Pr}_h(z)\frac{D_h}{L_h}\right]^{-2/3} \qquad (5)$$

The term $\left[\mathrm{Re}_h(z)\,\mathrm{Pr}_h(z)\frac{D_h}{L_h}\right]$ can be expressed as a function of $\phi\left[\mathrm{Re}_h(z=0)\,\mathrm{Pr}_h(z=0)\left(\frac{D_h}{L_h}\right)\right]$ with a factor of multiplication

$$\phi = \frac{C_p(z)k(z=0)}{C_p(z=0)k(z)} = \phi(T_h / T_{h1}) \qquad (6)$$

For engine oil with the aid of data from [5], the multiplication factor ϕ can be expressed as follows

$$\phi = \left[\frac{(1787.5 + 4.332T_h)}{(1787.5 + 4.332T_{h1})}\right]\left[\frac{0.1495 - 1.548x10^{-2}T_{h1} + 2.767x10^{-7}T_{h1}}{0.1495 - 1.548x10^{-2}T_h + 2.767x10^{-7}T_h}\right] \qquad (7)$$

Thus, for constant wall temperature condition equation (4) becomes highly non-linear and it can be expressed as follows:

$$-\left[\frac{dT_h}{T_h - T_W}\right] = 4x1.86\,[\phi\lambda_1]^{-2/3}\, d\left[\frac{z}{L_h}\right] \qquad (8)$$

where

$$\lambda_1 = \mathrm{Re}_h(z=0)\,\mathrm{Pr}_h(z=0)\frac{D_h}{L_h} \qquad (9)$$

Cold Fluid (air)

The heat transfer on the cold fluid side can be estimated from equation

$$Nu_C = 1.9656\ Gz_C^{0.333} \qquad (10)$$

$$\frac{dT_C}{T_c - \eta_f T_w} = \left[\frac{h_c\ \pi D_c}{m_c C_c}\right] dz = \frac{4Nu_c}{\mathrm{Re}_c\,\mathrm{Pr}_c(D_c/L_c)} d\left[\frac{z}{L_c}\right] \qquad (11)$$

where $Nu_c = 1.86\left[\mathrm{Re}_c\,\mathrm{Pr}_c\,\frac{D_c}{L_c}\right]^{0.333}$

Thus equation (10) can be simplified as follows

$$\left[\frac{dT_C}{T_c - \eta_f T_w}\right] = 4x1.86\,[\lambda_2]^{-2/3}\, d\left[\frac{z}{L_c}\right] \qquad (12)$$

Where

$$\lambda_2 = \mathrm{Re}_c\,\mathrm{Pr}_c(D_c / L_c) \qquad (13)$$

η_f is the fin efficiency corresponding to the triangular ducts through which coolant air is force drafted

Besides, the energy balance between the hot and cold media should satisfy the condition

$$G_c C_c (T_c - T_{c1}) = G_h C_h (T_{h1} - T_{h2}) \qquad (14)$$
$$where\ G_C = N_1 \dot{m}_C : G_h = N_2\,\dot{m}_h$$

Thus, the formulation is complete in respect of evaluation of the outlet temperatures of hot and cold fluids for given inlet Re_h and Re_c

Numerical Method of Evaluation

The following iterative procedure is employed step wise:

1. Q_h , V_c , $T_h(I=1)$, $T_C(I=1)$, L_h/D_h, L_c/D_c and η_f are prescribed
2. Equations (8) and (11) are written in finite difference form respectively as follows

$$T_h(I+1) = T_h(I) - 4 \times 1.86[\phi(I)\lambda_1]^{-2/3}\{T_h(I) - T_W\}\Delta\eta \qquad (15)$$

$$T_c(I+1) = T_C(I) - 4 \times 1.86[\lambda_2]^{-2/3}\{T_C(I) - \eta_f T_W\}\Delta\eta \qquad (16)$$

Where 1<I<J and J=11 is prescribed and $\Delta\eta = \frac{1}{J-1}$

$T_h(1)$ and $T_C(1)$ are the hot and cold media at inlet of heat exchanger.

For an assumed value T_W, wall temperature approximately $0.6[T_h(1) + T_c(1)]$ $T_h(I=J)$ and $T_C(I=J)$ are determined from equation (15)and (16)

3. With these computed values the energy balance i.e equation (14) is verified with error criteria defined as

$$\text{Error}=\left[1-\frac{G_c(T_C(I=J)-T_C(I=1)}{G_h(T_h(I=1)-T_h(I=J)}\right]100\ \% \qquad (17)$$

If ERROR< 0.1%, the mean wall temperature T_W for prescribed, η_f ,Q_h, V_c is assumed to converge and the salient output is printed for the inputs G_h,G_c ,$T_h(1)$,$T_C(I=J)$.ε

4. If convergence is not achieved, a linear interpolation technique is employed till convergence is obtained for the prescribed accuracy by following steps 1 to 3.

RESULTS AND DISCUSSION

For the flying ranges of altitudes of aero engine between 0 to 30000ft, the thermo physical properties of air are evaluated at temperatures from the information available in the www.aerospaceweb.org / The properties are rendered into correlations which are subsequently employed in the programs. Besides the properties of engine oil are also assessed for the ranges of temperatures from 60 to 140°C.

Thus following the computational procedure outlined the heat exchanger effectiveness and other relevant characteristics are shown plotted in figures 2-11. In the Figures 2, 3 and 4 the coolant air velocity is altered at three typical altitudes of 7000ft, 10750ft and 22500ft. The respective inlet temperatures of coolant respectively at these altitudes will be -0.1 °C, -6.3 °C and -29.5°C. The effectiveness of the heat exchanger is found to be profoundly influenced by the altitude of the flight as evident from figures (5), (6),(7). On the same plots the effectiveness variations as per the computations from the heat transfer hand books are also indicated. Evidently, the deviation between present theoretical study and the empirical equations of the data book is found to be quite substantial for identical system parameters. Hence for design considerations a dimensionless correlation applicable to the present configuration of the aero heat exchanger is carried out.

Computer runs are accomplished for wide ranges of Reh, Re_c within laminar ranges for flow conditions of the media and the data are further subjected to regression analysis to obtain a correlation as follows.

$$\varepsilon = 1.61[N.T.U]^{0.19}\ \mathrm{Re}_C^{-0.241}\ \mathrm{Re}_h^{-0.0187}\ \varepsilon_1^{0.5643} \qquad (18)$$

ε_1 is to be computed from equation(1)

The correlation (see plot Fig8) satisfies the analytical value from the runs with an average deviation of 0.586% and a standard deviation of 0.724%

The predictions from the correlation (18) agree well with the theoretical values as evident from figure-9, 10 & 11.The continuous solid line in the plots are from the theory and the solid symbols are computations from the correlation[18)

Conclusions

Thus the following conclusions can be arrived from the analysis.

1. The effectiveness of the heat exchanger will be affected by the altitude of the flight. It is seen that the effectiveness increases with the altitude.
2. It is observed that the thermo physical properties vary with the altitude and hence the effectiveness of the heat exchanger in turn is also found to be a function of Re_h, Re_c, NTU, C_{min}/C_{max}.
3. The effectiveness of the heat exchanger can be calculated from equation (18) for the particular heat exchanger.

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Figures

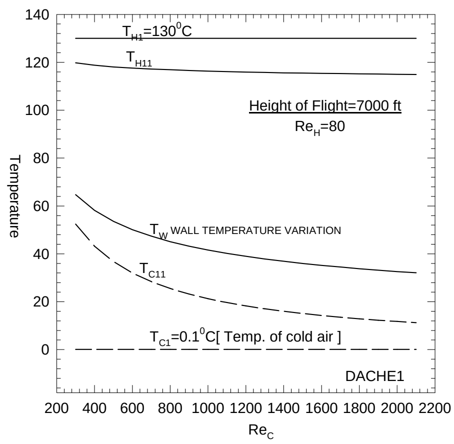


Fig2. Variation of hot and cold fluid temperatures at height of 7000 ft

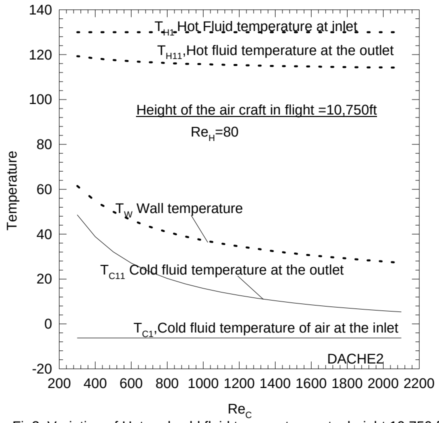


Fig3: Variation of Hot and cold fluid temperatures at a height 10,750 ft

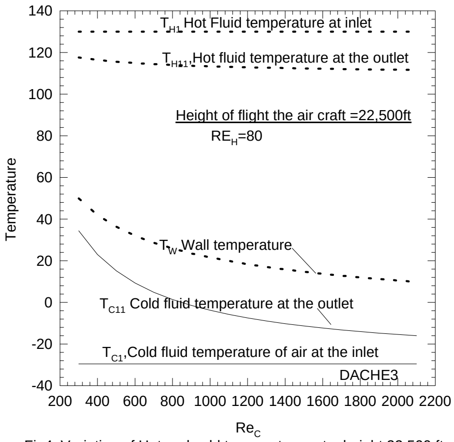


Fig4: Variation of Hot and cold temperatures at a height 22,500 ft

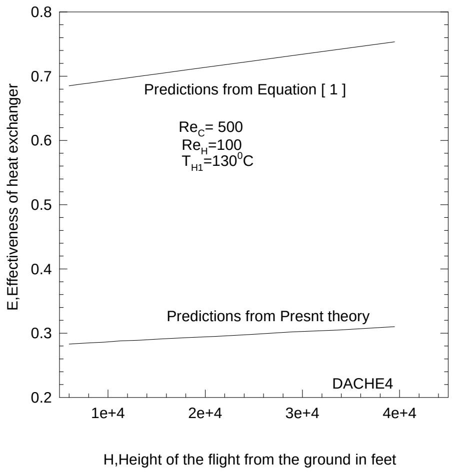


Fig5: Comparison of Present analysis with Equation from Hand book

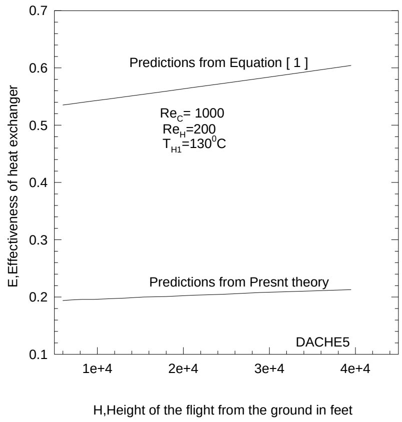


Fig6: Comparison of Present analysis with Equation from Hand book

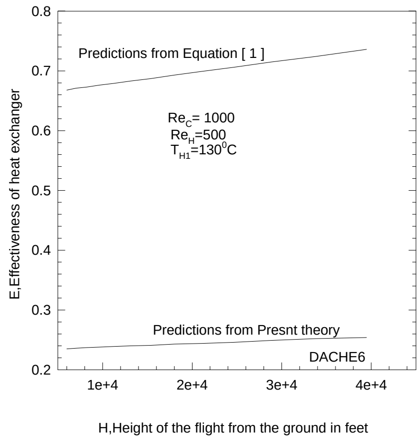


Fig7: Comparison of Present analysis with Equation from Hand book

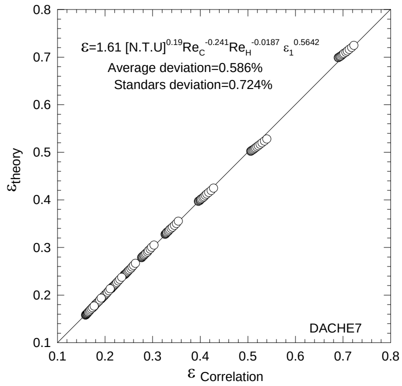
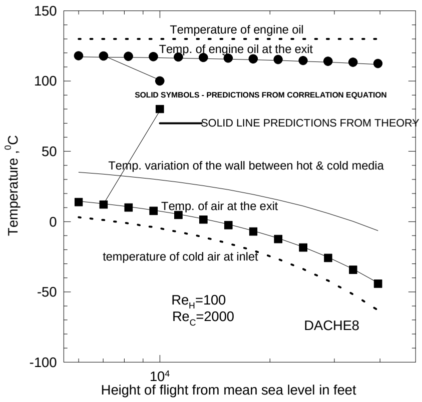
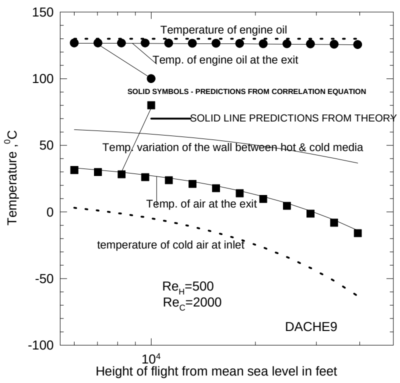


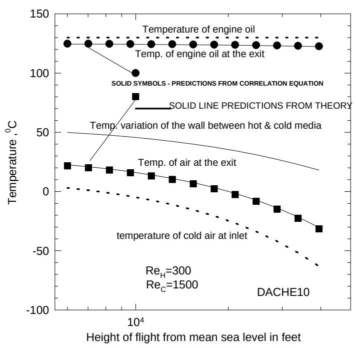
Fig 8 Validation of the correlation



Height of flight from mean sea level in feet
Fig9 Variation of salient temperatures with height of flight



Height of flight from mean sea level in feet
Fig 10 Variation of salient temperatures with height of flight



Height of flight from mean sea level in feet

Fig 11 Variation of salient temperatures with height of flight

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Nomenclature

A	Area, m^2
c	specific heat, kJ/kg K
C	C_{min}/C_{max} Ratio
D	Hydraulic Diameter, m
G	Total Mass flow rate, kg/s
Gz	Greatz Number, Re.Pr.(L/D)
h	Heat transfer coefficient , W/m^2 K
k	thermal conductivity, W/m K
L	length, m
M_C, M_H	Mass flow rate of cold and fluid respectively in each channel, kg/s
N_1	Number of cold channels
N_2	Number of hot channels
NTU	Number of Transfer Units, $[UA/C_{min}]$
Nu	Nusselt Number, [hD/k]
P	Perimeter, m
Pr	Prandtl Number
Q	Volume flow rate, LPM
Re	Reynolds Number
t	Thickness of the fin, m
T	Temperature, ^{0}C
W	Width of the fin, m
N1	Number of triangular ducts
Z	Distance along the length, m

Roman letters

ε	Effectiveness
η	Efficiency

Subscripts

1	inlet
2	outlet
C	cold fluid.
f	Fin
h	hot fluid
w	wall