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Optimization Of Recuperative Heat Exchanger In Gas Turbine

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ABSTRACT

Today the needs for safer, cleaner and more affordable civil aero engines are found to be of great importance. Few years ago, the EU initiated an action for the design and the construction of Efficient and Environmentally Friendly Aero Engines. The present paper is about a similar technology for development of advanced aero engine design, which uses alternative thermodynamic cycle (references [1]). Thermal efficiency and fuel economy are most important in gas turbine design. Recuperative heat exchanger will be used to increase combustor inlet temperature. This work therefore focuses on the analysis of the recuperative heat exchanger modeling and simulation of heat distribution in the exchanger. The benefits of this technique are focused on reduced pollutants and decreased fuel consumption. Present work, describes an effort to model the operational system of recuperative heat exchanger (RHE) for real engine operating.

In aero engine gas turbine heat exchanger is one of the major component common in handling thermal energy process. Improvement of optimized heat exchanger affect in the performance of gas turbine in directly or indirectly.

Boundary conditions for thermal analysis consist of fluid (air side and hot gas side) temperatures, mass flows and heat transfer coefficients. The heat transfer coefficients on the air side are determined by the correlations for fully developed turbulent flow in ducts and the gas side correlations for flow over tube are used.

The performance of Heat exchanger is discussed with different number of profile tubes, gas flow rates, overall heat transfer coefficient and different flight conditions.

The thermal analyses are correlated to the theoretical measurements. A preliminary 2D FEA modeling for the flow through turbine exhaust duct and the heat exchangers is considered. It is shown that with a careful approach, a better arrangement of the heat exchangers can be achieved in order to have a better efficient HE usage and positive effect on the engine's performance.

This paper explains about simple modeling of the recuperative heat exchanger with ANSYS FE Modeling using LINK34 and FLUID116 elements. LINK34 acts as a metal element between cold & hot gases (FLUID116). An overall Heat transfer co-efficient (HTC) is calculated based on the size, shape & dimensions of the heat exchanger and also flow parameters such as flow rate & gas material properties.

This ANSYS FE modeling technique using LINK34 elements for solid material is far less time consuming & effective in optimizing the heat exchanger design than that of the conventional method of modeling the solid elements with SOLID70, SOLID87 or SOLID90. And also this technique will reduce time taken for solution run.

Keywords:

Recuperative Heat Exchanger (RHE), Gas flow, Heat Transfer, Heat Transfer Coefficient (HTC), High Pressure Compressor (HPC), LINK34, FLUID116, Turbine Exhaust gas temperature.

1. INTRODUCTION

The positive effect in global economy due to easy transformation/mobility of millions across world due to development in aeronautical filed. Significant efforts for evolution of aero engines are focused on reduction of fuel consumption and pollutant emissions. Latest innovative ideas are being investigated in industry to improve aero engine performance and fulfill strict environmental requirements of fuel consumption and pollutant emission.

In order to decrease fuel consumption and emission significantly worked out air after the HPC is fed into the recuperator where the hot exhaust gases from the turbine exhaust gases are been allowed to pass in counter direction. The net impact of these cross flow guarantees a high potential raise in temperature of the air from compressor which is passed to combustion chamber to generate thrust. Literature survey reveals that by this method fuel consumption up to 20% can be attained against current aero engines over a large range of speeds. Due to the thermal performance and weight constraints of the new components, the thermal design of the recuperator is very important for the overall gain in efficiency of the complete engine. The basic design of the heat exchanger was developed by MTU some time ago (reference [3]).

Combustion generates heat and recuperator serves to reclaim this heat in order to reuse or recycle it.

- In a gas turbine, air is compressed, mixed with fuel, burned and used to drive a turbine.
- Recuperator transfers some waste heat in exhaust to compressed air, thus preheating it before entering the combustor.
- Since gases are preheated, less fuel is needed to heat it up to turbine inlet temperature.
- By recovering some energy usually lost as heat, it makes the gas turbine more efficient

2. GAS TURBINE RECUPERATIVE HEAT EXCHANGER

It is an indirect contact type U-shaped tubular cross counter flow heat exchanger.

- It consists of two manifold tubes.

- The flow from HPC enters upper tube (distributor) from both sides and is distributed into U-shaped profile tubes, which are brazed into manifold tubes.
- Lower manifold tube (collector tube) collects preheated air and leads it back to combustion chamber.
- Hot exhaust gas from LPT flows upward through matrix and is cooled while heating air inside profile tubes.
- Profile tubes are folded from sheet metal and welded at their mating faces.
- They are bent into U-shapes and each profile is a part of a tube set.
- All the parts of heat exchanger are made of INCONEL 625 except the wire spacing and cushion wire netting where INCO600 material is used.
- A cover of sheet metal is placed around the matrix to stabilize the package and adds damping to the system

While the flow passes U-bend of tube, it loses pressure in addition to the pressure loss caused by straight tube. The total pressure drop in a bend is the sum of the frictional head loss due to the length of the bend and head loss due to curvature (reference [4]).

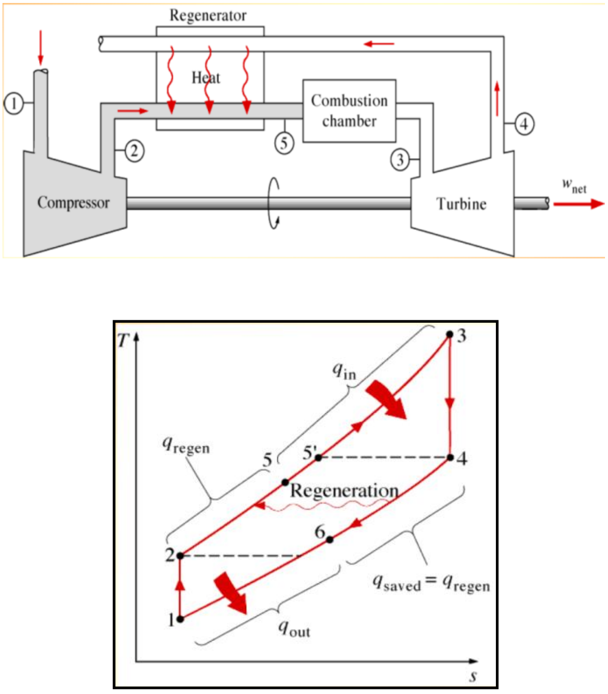

Fig 1: Gas Turbine Cycle with Recuperator Heat Exchanger

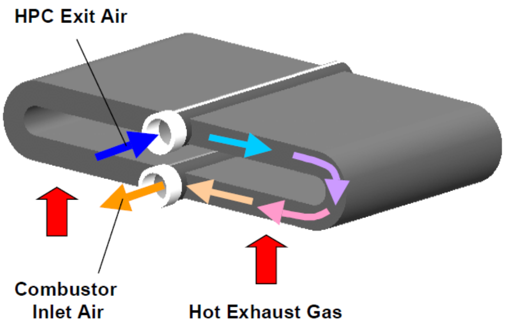

Fig 2: Recuperator (Source (Reference [2])

3. RECUPERATOR WEIGHT

Important for any aeronautical applications is the effect of engine weight. The additional components add to the overall engine weight: the intercooler and relative ducts, the additional third nozzle, and especially the recuperator and the piping system between HPC exit and recuperator modules. Preliminary weight estimations for the recuperator and its accessories have to be carried studied, for various geometrical arrangement for an efficient design. The high total weight of the heat exchanger system is a challenge for an aeronautical application and leaves room for improvement and for an optimization of the arrangement (references [2]).

To counter-balance these benefits, there are increased complexity in the engine construction, additional expensive components and additional reliability and life issues associated with the high temperature loads and the new heat exchanger modules. Any additional component contributes to the increased total engine weight, while high-technology modules (especially the two heat exchangers and the variable geometry turbine system) would contribute to a general increase of manufacturing and maintenance costs. Such economic penalties must be balanced against better operating costs, deriving from lower fuel consumption and from potentially lower landing fees (references [2])

BENEFITS OF USING RECUPERATIVE HEAT EXCHANGER:

- Reduction of fuel consumption up to 20% by increasing combustion chamber inlet gas temperature
- Reduction of pollutant emissions because of more efficient combustion
- Overall gain in efficiency of the gas turbine engine.

4. FINITE ELEMENT MODEL

A two dimensional finite element model is created using ANSYS 12.1 as shown in Fig 3. FLUID116 elements are used for flow (total of 168 elements). Thermal contact at the between two counter pipes are considered using LINK34 elements to apply the effective heat transfer coefficient

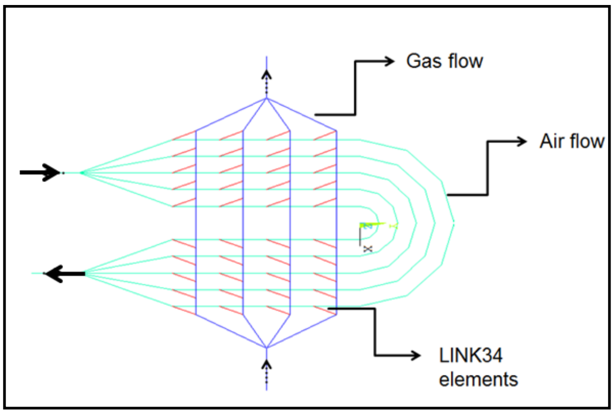

Fig 3: Heat Exchanger Finite Element Model

To introduce flexibility into the model generation, so that future changes in the model could be easily facilitated in the thermal modelling. A program was written in the ANSYS programming language, APDL, which automatically generates a finite element model.

In addition to the geometric parameters, some additional parameters are defined to specify flow, both on the air and gas sides of the flow path, to facilitate the automatic generation of the thermal and convective boundary conditions for the finite element model. More work needed to develop this program to be able to automate and studies can be carried further

5. Thermal Boundary Conditions

Mass flow, temperatures and heat transfer coefficients of fluid (HPC worked air side and hot exhaust gas side) are considered as boundary conditions for the thermal analysis. Inlet temperatures are specified at the two fluid nodes only, namely for air and gas inlet temperatures. With specified mass flow distributions.

Inlet air and gas temperatures are based on assumed aero engine performance. The data at recuperator inlets are tabulated in Table.1. The heat transfer coefficients on the air side it is determined by correlations for turbulent flow inside circular tube. Gas side it is determined correlations for flow over cylinders. Radiation is not accounted for in the model; however, at the temperature levels and temperature distribution encountered in the matrix, radiative heat transfer may be neglected. Effective heat transfer rate is computed and been considered using Link34 elements to compute convection (between tube & gas) and conduction (between tube & tube).

For modelling convection due to leakage between the flanges and between bolts and nuts, the well-known Dittus-Boelter correlation is used (reference [5]).

Nu = 0.023 ReD0.8 Pr0.3 (1)

AIR SIDE Heat transfer co-efficient:

$$h_i = \frac{\text{NuK}}{D_i} \quad (2)$$

Velocity of gas through gaps; $V_{gi} = \frac{M_g/2}{\rho_g \times A_g}$ (3)

Prandtl number (Pr) = $\frac{C_p \mu}{K}$ (4)

Reynolds number (Re) = $\frac{D_o V_{gi} \rho_g}{\mu}$ (5)

GAS SIDE Heat transfer co-efficient:

$$h_o = \frac{\text{NuK}}{D_o} \quad (6)$$

Overall heat transfer coefficient:

$$U = \frac{1}{\left(\frac{1}{h_o}\right)+\left(\frac{t}{K}\right)+\left(\frac{1}{h_o}\right)} \quad (7)$$

Table.1: Initial thermal boundary condition

Side	Property	End Take-off	Max Climb	Avg.Cruise	Reverse	NO. of Profile tubes
Air	Mass flow ; lb/sec	15.1	5.3	3.7	9.2	2500
	Inlet Pressure ;psia	448	157	110	265	
	Inlet Temperature; °F	840	615	453	635	
Gas	Mass flow ; lb/sec	20.2	7.1	5.0	12.3	
	Inlet Pressure ;psia	24	8	6	18	
	Inlet Temperature; °F	1240	1191	1139	1196	

Using Table-1 Initial boundary conditions generated the thermals and discussed in results part

6. Thermal Results and Discussion

The main purpose of optimizing a recuperative heat exchanger is to increase the temperature of compressor exit cold air flowing through the profile tubes to maximum by extracting heat from the hot turbine exhaust gas.

Temperature calculations have been performed for different steady-state performance points such as 'Take-off, Maximum climb, Average Cruise, Reverse' using the commercial program ANSYS12.1/Thermal as solver. Heat transfer coefficients incorporated using 1D performance calculation of the aero engine, computed flow through pipe correlation, during an analysis run. The temperature contour is shown in Fig.4. Thermalcontours of grid are 840degF to 1240degF not uniform, varying considerably not only along the length of the profile tubes, but also across the tube bundle. The shown material temperatures are selected close to the stagnation point of the profiles. As can be seen the heat up of the profile tubes at different direction of air flow.

Here tried with different direction of flows entering through the Recuperator Heat exchanger (using 1500 profile tubes), and finally concluded with more effective direction of entering flow.

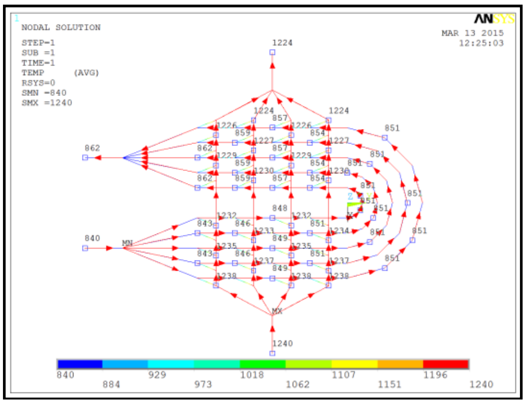

Fig 4: Inlet Air Enters From Bottom and Exit at Top

- Temperature increased of cold flow (air)=862-840=22 °F
- Temperature decreased of hot flow=1240-1224=16 °F

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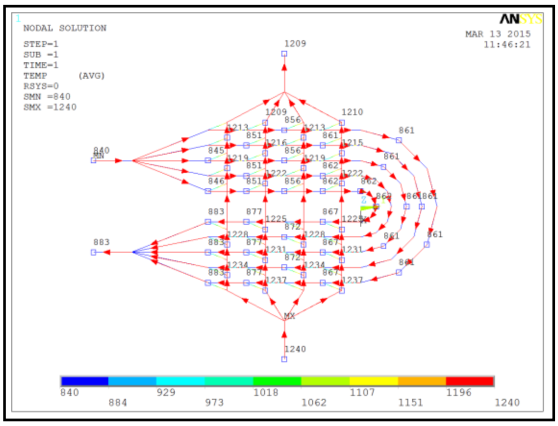

Fig 5: Inlet Air Enters From Top and Exit at Bottom

- Temperature increased of cold flow (air)=883-840=43 °F
- Temperature decreased of hot flow =1240-1209 =31°F

It is proved that Air Inlet Air Enters from Top and Exit At Bottom is the efficient direction of flow of air through profile tubes. The main reason behind this is when the cold air flows from bottom it extracts heat from hottest exhaust gas at the bottom. Due to this it does not possess further capacity to extract remaining heat from exhaust while flowing up. But when air flows from top to bottom, after extracting some heat from exhaust at top it possesses further capacity to extract heat at the bottom from the hottest exhaust gas.

Based on initial boundary condition perform the steady state thermal analyses

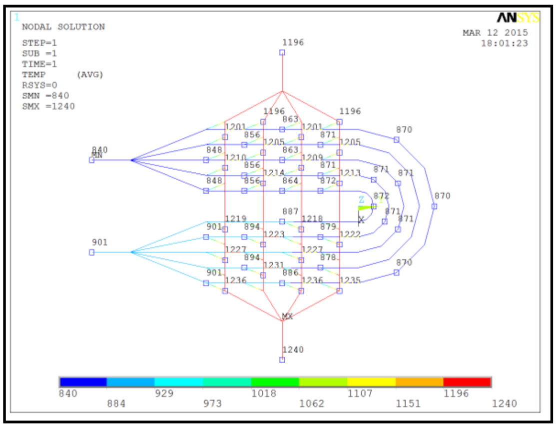

Fig 6: Temperature Contour at SS Take-Off Condition

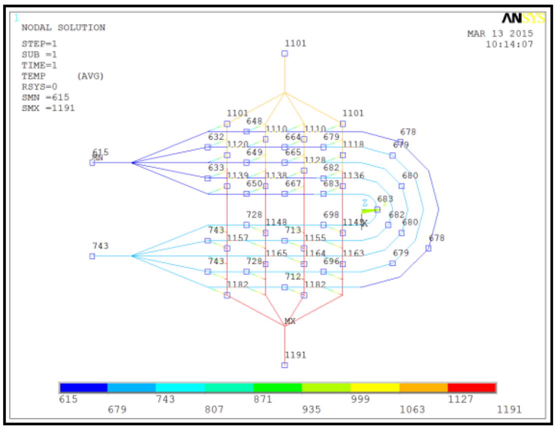

Fig 7: Temperature Contour atSS Max Climb Condition

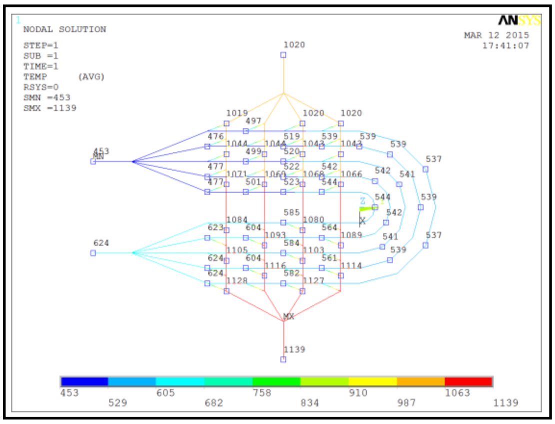

Fig 8: Temperature Contour atSS Avg Cruise Condition

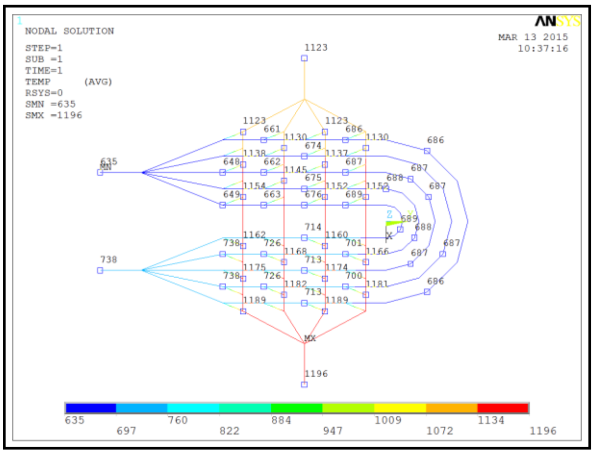

Fig 9: Temperature Contour atSS Reverse Condition

Table.2: Results for initial Boundary condition

	End Take-off	Max Climb	Avg.Cruise	Reverse
Profile tubes	2500			
Air side -Mass flow rate ; lb/sec	15.1	5.3	3.7	9.2
Gas side -Mass flow rate ; lb/ssec	20.2	7.1	5	12.3
T inlet(cold) ; °F	840	615	453	635
T inlet(Hot) ; °F	1240	1191	1139	1196
Overall HTC ; BTU/hr.(sq.ft).°F	126	103	84	142
Temperature increased of cold flow(Air); °F	61	128	171	103
Temperature decreased of Hot flow(Gas); °F	44	90	119	73

From the above different iteration results refer the Table-2 Recuperator with 2500 profile tubes can be most used most efficiently at Average Cruise condition. Since the maximum temperature difference i.e maximum efficiency is obtained at Average Cruise condition (cold flow=171 °F and hot flow=119 ° F) compared to other flight conditions.

7. Parametric Study on Changing Number Profile Tubes at SS Take-Off Condition

Sensitivity studies are carried out on the changing number of profile tubes at SS End Take-off conditions (Assuming that total mass flow rate is same). Based on number of tubes, the mass flow per tube is reducing while increasing the profile tubes. The increase in conduction area with increased number of profile tubes.

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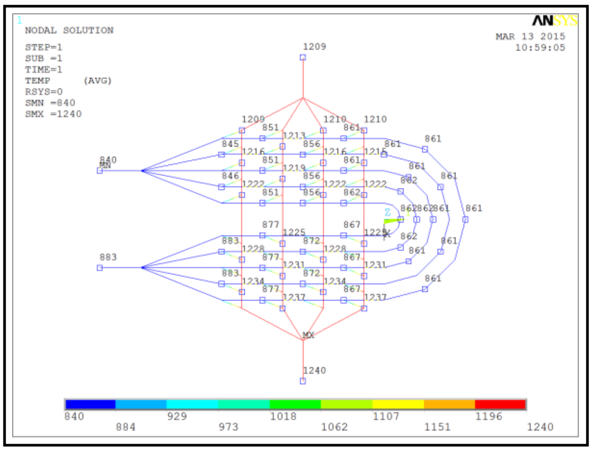

Fig 10: Temperature Contour atSS Take-Off Condition with 1500 Profile Tubes

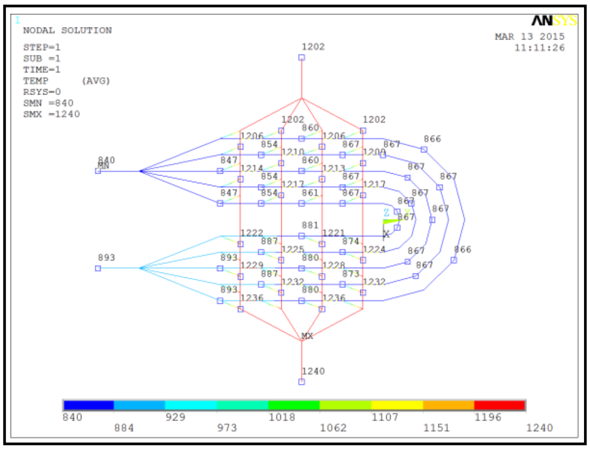

Fig 11: Temperature Contour atSS Take-Off Condition with 2000 Profile Tubes

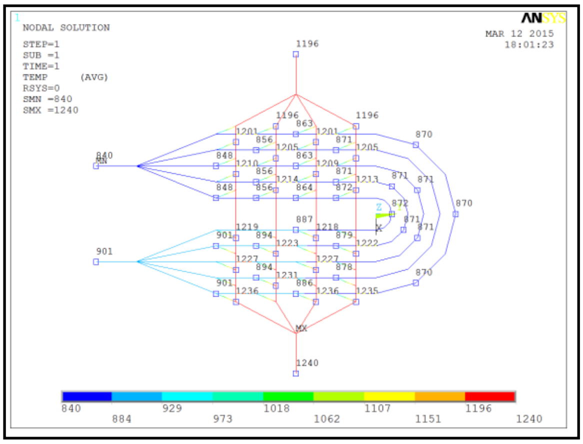

Fig 12: Temperature Contour atSS Take-Off Condition with 2500 Profile Tubes

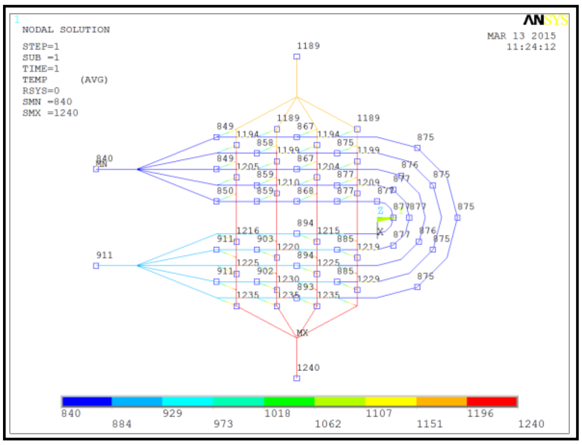

Fig 13: Temperature Contour atSS Take-Off Condition with 3500 Profile Tubes

Table.3: Sensitivity studies at End Take-off condition

END TAKE-OFF condition				
	Iteration-1	Iteration-2	Iteration-3	Iteration-4
Profile tubes	1500	2000	2500	3500
Air side -Mass flow rate ; lb/sec	15.1			
Gas side -Mass flow rate ; lb/ssec	20.2			
T inlet(cold) ; °F	840			
T inlet(Hot) ; °F	1240			
Overall HTC ; BTU/hr.(sq.ft).°F	126	162	191	227.9
Temperature increased of cold flow(Air); °F	43	53	61	71
Temperature decreased of Hot flow(Gas); °F	31	38	44	51

Here observation is if increasing the number of profile tubes, Exit air temperature also increasing.

8. Conclusion

In the present work the modelling of the operation of a system of recuperative heat exchangers of aero engine was performed for real engine operating conditions.

Design of recuperator heat exchanger was optimized by taking several factors into consideration. These factors will affect the performance of the heat exchanger and the gas turbine engine. The parameters considered for optimizing the performance of recuperator heat exchanger are:-

1. Direction of flow of cold air in the profile tubes.

Temperature of cold fluid (air) increased by

- 22 °F when air enters through inlet at bottom and exit at top
- 43 °F when air enters through inlet at top and exit at bottom

Hence the efficient direction of gas flow is when air enters through inlet at top and exit at bottom through profile tubes

2. Optimum condition for recuperator heat exchanger at End Take-Off condition.
   - It is when the recuperator has 2500 tubes at constant distributor tube length (0.5m), providing comparatively high temperature difference (cold flow=61°F, hot flow=44°F) at the same time remaining within dimensional specification.
3. Condition at which (End Take-Off, Max Climb, Avg. Cruise, Reverse) recuperator can be used most efficiently.

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- Since the maximum temperature difference i.e maximum efficiency is obtained at Avg. Cruise condition (cold flow=171°F and hot flow=119°F) compared to other flight conditions, tubes can be used most efficiently at Average Cruise condition.

The use of inter-cooling and heat recuperation in aero gas turbine engines has been studied and continued in order to investigate the potential for emission and fuel consumption reductions.

9. ACKNOWLEDGMENT
I would like to thank my colleagues and my family for their contribution and support at all time.

10. NOMENCLATURE

HPC	----	High Pressure Compressor
HTC	----	Heat Transfer Co-efficient
K	----	Conductivity
LPC	----	Low Pressure Compressor
M	----	Total mass flow rate
Re	----	Reynolds Number
Pr	----	Prandtl Number
U	----	Overall Heat transfer Co-efficient
h_o	----	Gas side HTC
ρ	----	Density
μ	----	Viscosity
Nu	----	Nusselt Number
SS	----	Steady State

<u>Subscripts</u>

D	Diameter
i	Inner
g	Gas
o	Outer
gi	Gas through gaps

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