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CFD Simulation of Micro Gas Turbine (MGT) Recuperator

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To achieve high thermal efficiencies for micro and mini gas turbines a recuperator is mandatory. The present study investigates the flow and heat transfer characteristics of corrugated duct for the primary surface annular recuperator applications. Commercial CFD code is used to understand the variation of the overall flow structures and heat transfer parameters inside the corrugated duct. The effects of corrugation angles and flow directions with respect to inlet boundary are examined systematically, and the heat transfer and pressure loss characteristics are investigated. In order to arrive at a suitable mesh size, the grid sensitivity test has been carried out with three different grids. Optimum grid was selected based on convergence criteria, computational time and grid independent results. Finally attempts are made to increase the compactness of the recuperator. Corrugation angle 45^0 gives higher effectiveness when compared with 60^0 ,75^{0}angles.

Introduction

Following the deregulation of the electricity market in many countries there has been a massive interest in much smaller and more efficient micro and mini gas turbines (approximate output power ranges from 5 kW to 500 kW) for the Distributed Generation (DG)[1]. The small turbines enable small energy consumers to generate their own electricity. Micro turbines can meet the total energy needs for a variety of complexes including hospitals, supermarkets, schools, factories, office buildings and apartment houses. The advantages of the gas turbine prime-mover over existing Diesel engine generator sets include the following: smaller size and weight, multifuel capability, lower emissions, lower noise, vibration-free operation and reduced maintenance. About a dozen companies all over the world are currently involved in the development of micro turbines towards the goal of penetrating the commercial market starting around the year 2000. In India National Aerospace Laboratories, Bangalore has taken up development of 10 kW recuperated micro gas turbine.

In general, power plants and micro turbines systems are designed to obtain high effectiveness and low pressure losses, minimum volume and weight and high reliability and low cost (McDonald and Wilson, 1996). In order to achieve enhanced heat transfer, corrugated channels are often employed in the design of plate heat exchangers. Because of flow interruption including recirculation and reattachment, the heat transfer characteristics are quite different than flat plates[2] . This type channels interrupt the thermal boundary layer and thereby increase the convection heat transfer coefficient [3] . Corrugated channels are one of the very popular channels that are developed to improve heat transfer performance. Because these channels can lengthen the flow path and cause better mixing, higher heat transfer performance is obtained compared to straight ducts[4,5] . Corrugated duct is a good alternative for high heat flux applications or for more efficient heat exchange devices used in a wide variety of engineering applications like heating and air conditioning units.

Problem definition

The recuperator geometry was formed by single spool of thin foil which was stamped and folded to make passages for air and gas flow as shown in figure above. This folded geometry was press fitted between two hallow cylinders and it was welded at the ends the air passages at the both ends were closed by flanges. Gas enters the recuperator at one end and flows axially along the length of recuperator where as air enter the recuperator from opposite end radially through elliptical holes formed at the both ends of the recuperator radially the air takes a longitudinal path along the length of recuperator and comes out of it again through elliptical passage by fallowing a radial path. A preliminary design has been carried out to get the geometry of the recuperator. Total numbers of passages are 100 .Of them 50 are air passages and 50 are gas passages. Existing recuperator has less effectiveness and compactness. In redesign, straight plates are replaced by corrugated plants for increasing effectiveness and compactness of the recuperator.

SPECIFICATIONS OF THE MODEL

Ratio of outer diameter to inner diameter of recuperator : 1.345
Ratio of outer diameter to length of recuperator : 1.65.
Air inlet ellipse major diameter to minor diameter ratio : 2.5.
Distance between the two ellipses centers : 0.11836 m.
Ratio of length to wall thickness of recuperator : 280
Ratio of air passage to gas passage angle :1.25.
Number of air and exhaust gas Passages : 100(50+50).
Hydraulic diameter of air Passage : 0.01051 m.
Hydraulic diameter of gas Passages : 0.008574 m.
Air side heat transfer Coefficient : 62.66 W/m^2-K.
Exhaust gas side heat transfer Coefficient : 82.37W/m^2-K.

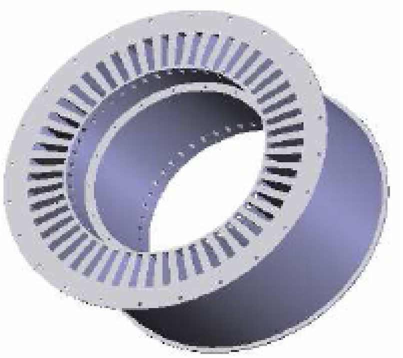

Figure-1: Annular Recuperator

Modeling and redesign

Due to the symmetric nature annular recuperator (see figure1) a sector model was taken for simulation. Figure 2 and 3 gives the sector model of existing recuperator with out and with meshing respectively.

Modeling and meshing of existing sector (gas-air-gas) model:

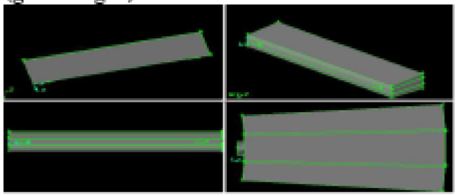

Figure-2: Modeling of existing sector (gas-air-gas) model:

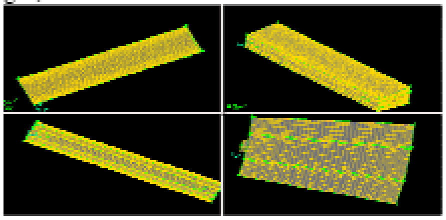

Figure-3: Different views of sector (existing) model with meshing.

REDESIGN

In the redesign, straight plates of recuperator are replaced by corrugated plates. The surfaces considered in this study have passive enhancement of the heat transfer process as opposed to active (surface vibration, electrical fields, etc.!) enhancement techniques. In the passive techniques secondary flow structures are created by means of curved and interrupted duct surfaces. The secondary gas and air flow structures in heat exchangers disturb the insulating near wall layers and thus improve the thermal exchange process in the duct.

Flow Regimes inside corrugated plates

Reynolds	Regime	Note
$20 < Re$	Laminar	
$20 < Re < 100$	Laminar	Stabilized recirculation
$100 < Re < 200$	Transitional	Instable recirculation
$200 < Re < 2000$	Transitional	Vortices (Von Karmann instabilities)
$Re > 2000$	Turbulent	

Profile of the corrugated geometry considered was sine curve. Important parameters those influence the design of corrugated recuperators are

1) Pitch-over-Height (P/H_i) ratio.
2) Corrugation Angle (γ).

1. Pitch-over-Height (P/H_i) ratio:

In general the range of P/H_i ratio used in design of corrugated recuperators is 2 to 4. As the pitch-over-height ratio increase heat transfer surface area decreases at same time pressure losses decreases. For a given P/H_i ratio, even though by changing the pitch of corrugated plates there will be no change in heat transfer surface area. Minimum Pitch-over-height ratio considered in the simulation was 2 because of the complications in manufacturing and for getting optimum ratio of heat transfer surface area to the pressure losses in the corrugated channels. Pitch of corrugations considered in the present work was 6 mm because of complications in inserting elliptical air inlet and outlet passages.

Generalized equation for measuring length of sin curve:

$$y = A\sin(\frac{2\pi}{P})x$$

$$\frac{dy}{dx} = \frac{2A\pi}{P}\cos(\frac{2\pi x}{P})$$

For small strip

$$ds^2 = dx^2 + dy^2.$$

$$ds = \sqrt{1+\left(\frac{dy}{dx}\right)^2}\,dx.$$

For particular pitch (P), integration above equation (between the limits 0 to P) gives length of curve :

$$\int_0^P ds = \int_0^P \sqrt{1+\left(\frac{dy}{dx}\right)^2}\,dx.$$

After substitution and simplification

$$\int_0^P ds = \int_0^P \sqrt{(1+(\frac{2\pi^2 A^2}{P^2})+(\frac{2\pi^2 A^2}{P^2})\cos(\frac{4\pi x}{P}))}\ \mathrm{dx}$$

.Where P= Pitch of sin curve.
$A(H_i)$=2*amplitude of sin curve.

1. Corrugation Angle (γ):

Corrugation angles considered in present simulations are $\gamma = 45^0, 60^0$ and 75^0(with respect to air longitudinal flow direction in the passages).

MODELING AND MESHING OF DIFFERENTCORRUGATED (45^0,60^0&75^0) ANGLED GEOMETRIES

Figures 4, 5 and 6 gives different sector views of corrugation angle (γ) 45^0 ,60^0 and 75^0 models with meshing respectively.

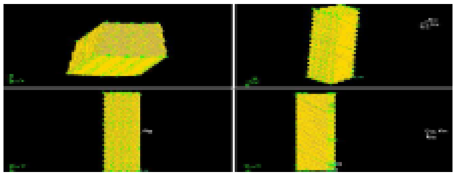

Figure-4: Different views of sector (Pitch=6 mm, $\gamma=45^0$) model with meshing

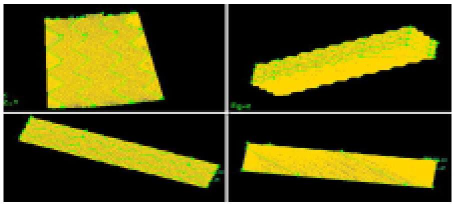

Figure-5: Different views of sector (Pitch=6 mm, $\gamma=60^0$) model with meshing

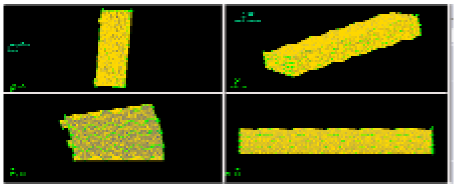

Figure-6: Different views of sector (Pitch=6 mm, $\gamma=75^0$) model with meshing

For increasing the compactness recuperator increase the total number of heat transfer walls with in the same vomlume.

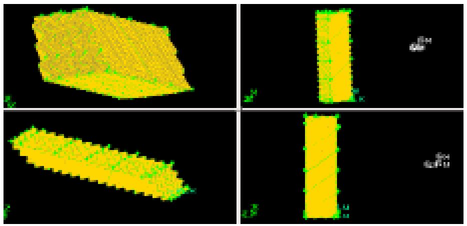

Figure-7: Different views of redesigned sector (80 air and gas passages) model with meshing.

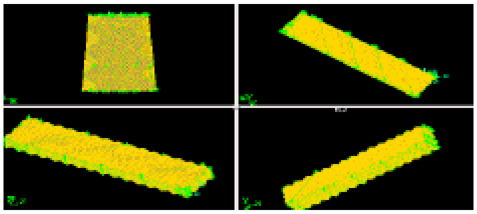

Figure-8: Different views of redesigned sector (100 air and gas passages) model with meshing.

Table-I: Air and Gas passage angles for 50, 80 and 100 heat transfer walls.

Number of passages (air&gas)	50	80	100
Air passage angle (deg)	4^0	2.5^0	2^0
Gas passage angle (deg)	3.2^0	2^0	1.6^0

RESULTS AND DISCUSSION

Figures 9 and 10 gives the simulation results (vectors) of existing model colored by temperature. From the figure 9 it can clearly observed that how the exhaust gases losses heat and from figure 10 it can be seen by color variation that how the air getting heated up while flowing through respective passages.

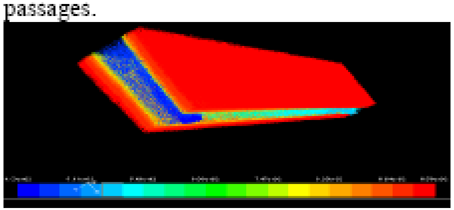

Figure-9: Vectors (colored by temp) of full sector (gas-air-gas) model

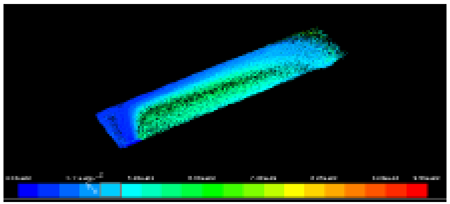

Figure-10: Vectors (colored by temp) of Air passage

Existing recuperator model (fig.2 and 3) was modeled and meshed in commercial CFD pre processor and simulated in commercial CFD solver.

The results obtained in the simulation of straight passage recuperator are:

- Outlet temperature of air coming from recuperator: 558.82 K.
- Effectiveness of recuperator: 0.26
- Relative total pressure loss: 3.63%.

From the results it is observed that effectiveness of recuperator is very less and at same time total relative pressure losses also lower than the allowable value of 5%. Hence we can increase the Heat transfer surface area and turbulence in the passages for better heat transfer argumentation.

SIMULATION RESULTS OF RE-DESIGN (PITCH= 6MM AND γ=60^0)

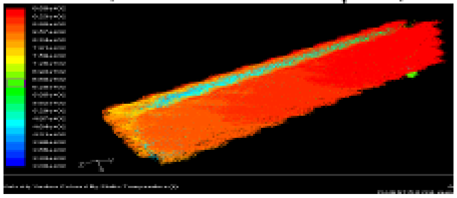

Figure-11: Velocity vectors (colored by temp) of full sector (gas-air-gas) model.

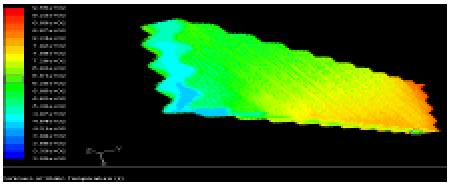

Figure-12: Temperature contours of Air passage.

VELOCITY VECTORS OF AIR PASSAGES (PITCH=6, γ=60^0) COLORED BY TEMPERATURE

The vectors and contours (Fig.11, 12, 13, 14 and 15) colored by temperature gives variation of heat transfer parameters for different flow directions (i.e. vertical, left and right) with respect to inlet boundary. Table 3 gives the temperature, effectiveness and total relative pressure losses for three directions.

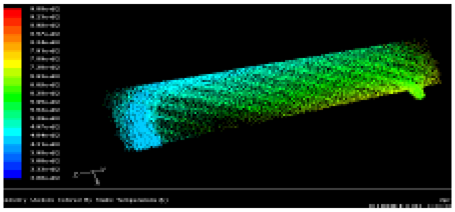

Figure-13: Inlet flow direction normal to boundary

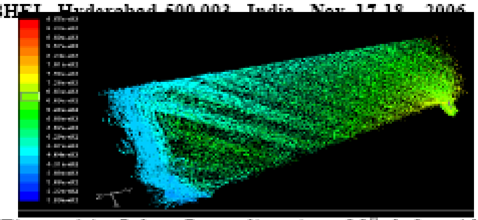

Figure-14: Inlet flow direction 30^0 left with horizontal

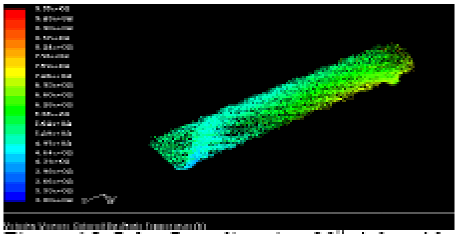

Figure-15: Inlet flow direction 30^0 right with horizontal.

Table-II: Effect of flow direction with respect to boundary on performance parameters.

Flow direction	Vertical	left	Right
Air outlet Temp(K)	657.43	667.63	658.83
Effectiveness of recuperator (ε)	0.43	0.45	0.433
Total relative pressure losses (%)	4.5689	5.2	4.652

From the Table II it can be observed that left directed flow (fig.14) gives better effectiveness at the same time total relative pressure losses are also high when compared with nominal value of 5%. It is also observed that right directed flow (fig.15) gives less effectiveness. Hence at this point it is concluded that directing the flow with particular direction gives high total relative pressure losses irrespective of the direction.

GRID INDEPENDENCE STUDY

In order to arrive at a suitable mesh size, the grid sensitivity test has been carried out with three different grids (fig.16). Grid independent study was conducted for corrugation angle 60^0 with (table.4) three different interval sizes (i.e. Interval size=1, 0.8, and 0.75). Optimum grid was selected based on convergence criteria, computational time and grid independent results.

Table III: Grid Independence study.

Interval size	1	0.8	0.75
No.of cells	440671	846082	1018178
AirTemp. at outlet of recuperator(k)	657.433	667.29	668.39

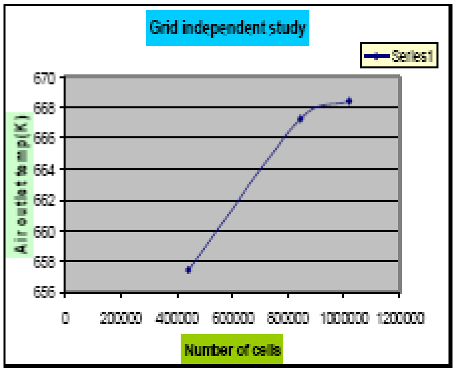

Figure-16: Number of cells vs. Air outlet temperature.

EFFECT OF CORRUGATION ANGLE

Table-IV and Figure-17 shows the effect of corrugation angle on the heat transfer parameters. Corrugation angle 45^0 gives higher effectiveness when compared to other two angles. From the table 5, we can conclude that the effectiveness is less and relative pressure losses are also with in limit of 5%. For improving the effectiveness and compactness of recuperator more number of fin (heat transfer) walls with in the same volume are suggested.

Table IV: Effect of corrugation angle on performance parameters.

Corrugation angle	45^0	60^0	75^0
Air outlet Temperature(K)	674.37	657.433	620.54
Effectiveness of recuperator	0.4626	0.43023	0.35965
Total relative pressure losses (%)	4.71541	4.5689	4.2365

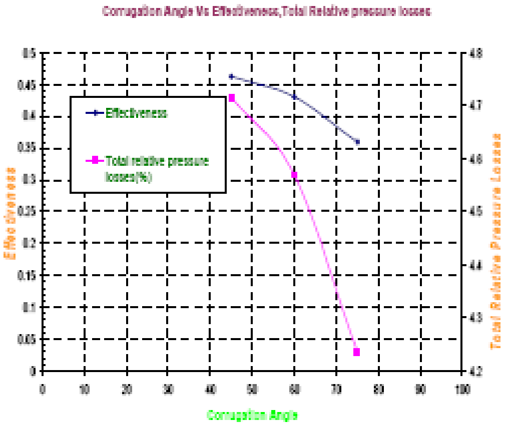

Figure-17: corrugation angle Vs effectiveness and total relative pressure losses.

Contours and vectors of 80 air and gas passages Model:

Figures 18, 19 and 20 give the contours and vectors (colored by temperature) of 80 air and gas passages model. From the figure 18(sector, gas-air-gas-air) it can clearly observed that how the exhaust gases losses heat and how compressed air (also see fig.19) getting heated.

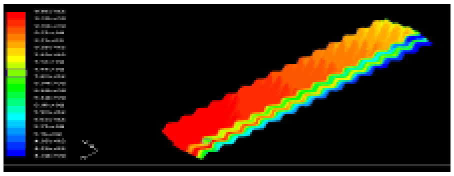

Figure-18: Vectors of sector (80 passages) model colored by temperature.

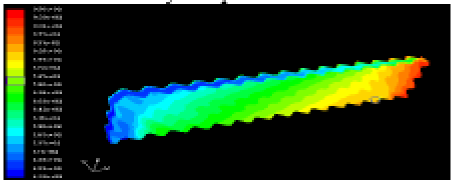

Figure-19: Contour of air passage (80 passages model) colored by temperature.

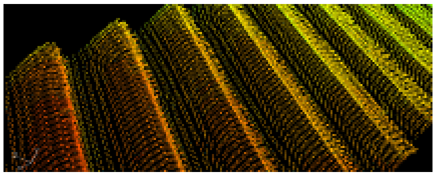

Figure-20: Vectors along the fin wall colored by temperature.

Contours and vectors of 100 air and gas passages Model

Figures 21, and 22 give the contours and vectors (colored by temperature) of 100 air and gas passages model. From the figure 21(sector, gas-air-gas-air) it can clearly observed that how the exhaust gases losses heat and how compressed air getting heated. Figure 22 gives the temperature variation of heat transfer wall of 100 air and gas passages model.

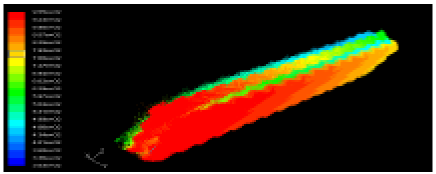

Figure-21 Vectors of sector (100 passages) model colored by temperature.

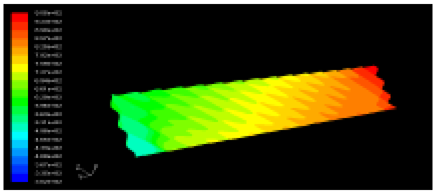

Figure-22: Fin wall temperature distributions for 100 passages.

The vectors and contours colored by temperature gives variation of heat transfer parameters for 80 air and gas passages model. The results of simulation are:

- Outlet temperature of air: 727.54 K.
- Effectiveness of recuperator: 0.563.
- Total relative pressure losses: 5.286%.

The vectors and contours colored by temperature gives variation of heat transfer parameters for 100 air and gas passages model. The results of simulation are:

- Outlet temperature of air: 776.84 K.
- Effectiveness of recuperator: 0.6583.
- Total relative pressure losses: 5.635%.

CONCLUSIONS

For Micro gas turbines a recuperator is mandatory for achieving higher efficiencies.

- Effectiveness of existing recuperator is 0.26 and total relative pressure losses (3.9%) are also with in permissible limit of 5%.
- Compactness of already existing recuperator is 256 m^2/m^3.
- In case of corrugated passages, corrugation angle 45^0 gives better effectiveness (0.4626) compared to other two angles (i.e. 60^0 and 75^0).Total relative pressure losses (4.7154) are also with in the permissible limit of 5%.
- Compactness of corrugated recuperator with 50 air and gas passages is 298 m^2/m^3.
- Effectiveness and compactness achieved in corrugated passages with 50 air and gas passages are very less and at the same time total relative pressure losses

also with in permissible limit of 5%. Hence for increasing effectiveness and compactness, more number of heat transfer walls with in the same volume are to be inserted.

NOMENCLATURE

γ	Corrugation angle (deg)
P	Pitch (mm)
H_i	Internal height (mm)
ε	Effectiveness
C_{pa}	Specific heat of air (J/kg K)
C_{pg}	Specific heat of gas (J/kg K)
μ_a	Viscosity of air
A	2*amplitude of sin curve (mm)
m_a	Mass flow rate of air (kg/s)
m_g	Mass flow rate of gas (kg/s)

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