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Comparative analysis of cylindrical and helical coil counter flow type of heat exchanger used in thermoelectric generator for waste heat recovery using CFD fluent

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Abstract- Proposal of two models to predict the performance of counter flow type heat exchanger used in thermoelectric generator for waste heat recovery is done on this paper. Comparison is done between helical coil and cylindrical counter flow type heat exchanger of same dimension and material to recover the waste heat by exhaust flue gases coming from engine using CFD fluent Work bench16.0 and design done on Siemens NX 8.0, which one is better suitable in thermo electric generator. Nitrous oxide is used as the main constituent exhaust gas where as cold atmospheric air act as inlet. Heat recovery system (HRS) helps to generate power which supplies additional functions for automobile accessories. HRS based on seebeck effect principle generates power. CFD fluent analysis is done during idling condition of exhaust nitrous oxide gas with assumption of fixed mass flow rate. Analysis of heat transfer rate is also shown for both models to show which configuration best suitable for idling condition of automobile. Analysis of temperature difference between gas and air is done for both geometrical configurations to correlate with electricity generation through seebeck effect.

Keywords: - CFD, Heat exchanger, Heat transfer rate, mass flow rate.

1. INTRODUCTION

Nearly 35-40% of chemical energy coming from fuel gone to exhaust gases which act as waste heat reduces thermal performance automobile and cause adverse effect on local atmosphere which further caused local global warming so here, proposed for two different geometrical configurations with same dimension to recover waste heat and converted into further for electric power generation [1].Low grade energy can be effectively convert using organic Rankine cycle [2].Advancement of thermoelectric material energy conversion of waste heat for power generation becomes popular topic [3].Challenges faced by automobile industries is heat exchanger meets requirement TE generator. Changes in heat exchanger geometrical configurations will be rejects more heat by a change of the over-all heat transfer coefficient UA due to which its thermal resistances will varies [4]. Parameters strongly depend upon working fluid, inlet temperature of fluids, velocity of fluids, mass flow rates for getting large temperature differences [5]. Studies have shown that improving simple heat exchanger configuration could extract more power. The electrical power generation is deeply influenced by voltage on the expense of temperature differences [6]. Zhang and Cleary conducted simulation of an optimum design of the heat exchanger, analysis done on CFD to obtain a maximum rate of heat transfer along with pressure drop found to be minimum [7].

2. GEOMETERY AND MESHING

Geometrical configuration of heat exchanger for thermal electric generators as shown in figure (1) of cylindrical heat exchanger and figure (2) helical coil heat exchanger counter flow. Inlet and Outlet boundary condition of fluids is shown in ansys each of 150 mm in length. Outer and inner tube of thickness 3 mm made up of steel material, nitrous oxide gas flows inside inner tube and air flows over the inner tube. Configuration details are illustrated in table1. Meshing condition as shown in table 2 with meshing figures are shown (3) and (4).

Table 1: Dimension of Configuration of Heat Exchanger

Cylindrical heat exchanger	Dimensions
Outer thickness of surface	3 mm
Inner thickness of surface	3 mm
Length of cylinder	150 mm

Outer diameter	15 mm
Inner diameter	10 mm
Helical coil heat exchanger	**Dimensions**
Outer thickness of surface	3 mm
Inner thickness of surface	3 mm
Pitch	30 mm
Radius	18 mm
Number of turns	4
Outer Diameter	15 mm
Inner Diameter	10 mm
Total length	150 mm

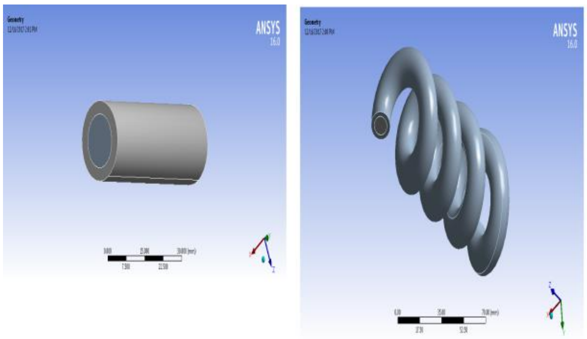


Figure 1: CHE configuration & Figure2. HCHE configuration in Ansys

Table 2: Meshing of Geometrical configuration

Features	Helical coil	Cylinder
Nodes	37456	14055
Elements	100153	10839
Minimum size	7.6055e-02 mm	7.551e-002 mm
Maximum size	7.60550 mm	7.5510 mm

Meshing is done on fine sizing with smoothing medium, relevance center coarse type is taken. Nodes and elements are higher for helical coil than cylindrical type.

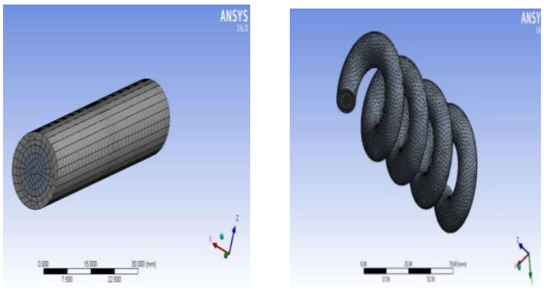


Figure 3: CHE meshing & figure 4: HCHE meshing

3. MATERIALS AND FLUIDS

Description of physical properties of material steel, fluids nitrous oxide gas and coolants as air is used as Table 3. Nitrous oxide as the main constituent for exhaust gases from automobile.

Table 3: Steel and Fluids

Steel	**Values**
Density, ρ (kg/m^3)	8030
Specific heat ,C$_p$(j/kg-k)	502.48
Thermal conductivity k ,(w/m-k)	16.27
Air	**Values**
Density, ρ(kg/m^3)	1.225
Specific heat, C$_p$(j/kg-k)	1006.43
Viscosity, μ(kg/m-s)	1.7894e-05
Thermal conductivity ,k(w/m-k)	0.0242
Nitrous oxide	**Values**
Density, ρ (kg/m^3)	1
Specific heat, C$_p$(j/kg-k)	880
Thermal conductivity, k(w/m-k)	0.0454
Viscosity,μ (kg/m-s)	1.72e-05

4. Turbulence model and boundary conditions

For modeling k-epsilon standard type on 3D model with scalable wall function, constant pressure turbulent kinetic energy, turbulent dissipation and energy equation are shown. Flow of both fluids with velocity of 10 m/s, having mass rate 0.01 kg/s, inlet gas temperature of 673 K along with inlet air act as coolant temperature of 300 K with conduction of 1 layer each of 3 mm flow direction is opposite to each other. Iteration on helical type having 1004 where as for cylindrical type 75 convergences gets. Model constant C_{mu} =0.09, $C_{1\varepsilon}$ =1.44, $C_{2\varepsilon}$ =1.92, σ_ϵ =1.3, σ_k=1.0, turbulent Prandtl along with energy number is taken 0.85 [8]

4.1. Turbulent kinetic energy k and its equation written as [9]

$$\frac{\partial(\rho\kappa)}{\partial t}+\frac{\partial(\rho\kappa u_i)}{\partial x}=\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\sigma_\kappa})\frac{\partial\kappa}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_m+S_k \quad \text{Eq. (A.1)}$$

4.2. Rate of dissipation ε and its equation written as [9]

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\mu+\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{\kappa}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{\kappa}+S_\varepsilon \quad \text{Eq. (A.2)}$$

4.3. Eddy viscosity (μ_t)

$$\mu t=\rho C\mu\frac{k^2}{\varepsilon} \quad \text{Eq.(A.3)}$$

4.4. Turbulent kinetic energy mean velocity gradient (G_k)

$$Gk=-\rho\overline{u'_\imath u'_\jmath}\frac{\partial u_j}{\partial x_i} \quad \text{Eq. (A.4)}$$

4.5. Turbulence due to buoyancy (G_b)

$$G_b=\beta g_i\frac{\mu_t}{Pr_t}\frac{\partial t}{\partial x_i} \quad \text{Eq. (A.5)}$$

4.6. Coefficient of thermal expansion (β)

$$\beta=-\frac{1}{\rho}\left(\frac{\partial\rho}{\partial t}\right)_p \qquad \text{Eq. (A.6)}$$

4.7. Fluctuating dilatant(Y_M) [10]

$$Y_m = 2\rho\varepsilon M_t^2 \qquad \text{Eq. (A.7)}$$

4.8. Turbulent Mach number(M_t) [11]

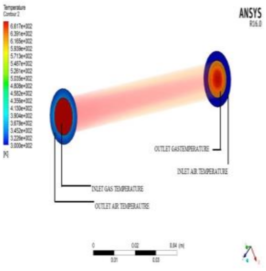
$$M_t = \sqrt{\frac{k}{a^2}} \qquad \text{Eq. (A.8)}$$

4.9. Speed of sound (a)

$$a=\sqrt{\gamma RT} \qquad \text{Eq. (A.9)}$$

5. RESULTS AND DISCUSSION

On given boundary a condition for both geometrical heat exchangers, effectiveness is calculated on the basis of that overall heat exchanger is being taken out. Comparison between helical coil type and cylindrical counter flow analysis is made $m_{nitous}\, c_{nitrous} < m_{air}\, c_{air}$. Figure (5) and Figure (6), after boundary conditions applied shows inlet and outlet temperature of nitrous oxide gas and air of CHE and HCHE. Figure (9) and Figure (10) Overall temperature distribution by rendering of CHE and HCHE.



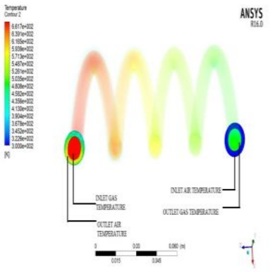


Figure 5: Output and Inlet temperature of air and nitrous oxide gas of CHE

Figure 6: Output and inlet temperature of air and nitrous oxide gas of HCHE

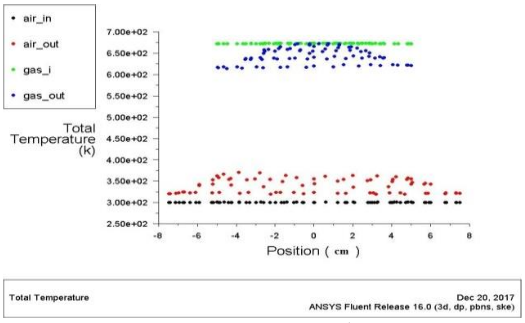


Figure 7: Temperature Vs position for CHE

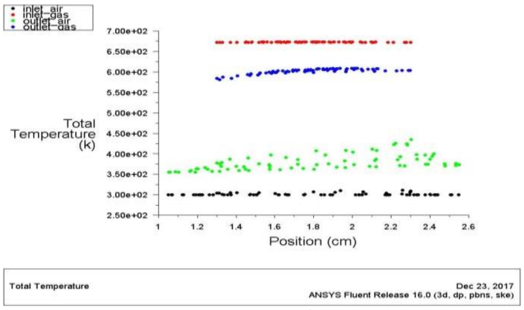


Figure 8: Temperature Vs position for HCHE

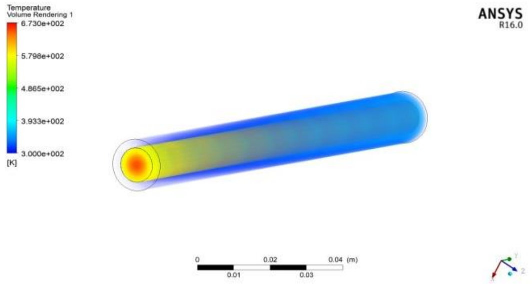


Figure 9: Temperature in CFD for CHE

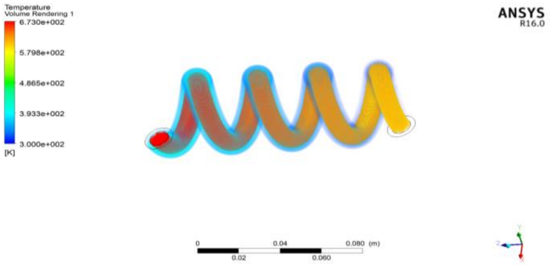


Figure 10: Temperature in CFD for HCHE

Effectiveness values of heat of two exchanger counter flow $(\varepsilon)_{\text{helical coil}} > (\varepsilon)_{\text{cylinder}}$. Overall heat transfer coefficient is taken out $(UA)_{\text{helical coil}} > (UA)_{\text{cylinder}}$. $(\Delta T_{lm})_{\text{cylinder}} > (\Delta T_{lm})_{\text{helical coil}}$. Heat transfer rate $(Q)_{\text{helical coil}} > (Q)_{\text{cylinder}}$.

5.1. Cylindrical heat exchanger(CHE)

Variation of temperature on each position as air passes over nitrous oxide gas separated by surface found because heat exchange surface area available for air outside is small as compared to surface available for nitrous oxide is large. It is not possible in CHE totally exchange heat from nitrous oxide to air because conduction of surface inner tube rate is slow and convection rate is low as $C_{(\text{nitrous oxide})} < C_{(\text{air})}$. As inner layer of nitrous oxide gas red in color show in figure (9) and position from x=-20 mm to x=-20 mm region there is no change in temperature found in figure (7).

5.2. Helical coil heat exchanger(HCHE)

Temperature difference found between inlet and outlet nitrous oxide gas is 100K along with inlet and outlet air over 140K. Circular turn on the same length achieves higher temperature gain by air x=120 mm beyond 420K as shown in figure (8).Heat exchanges drastically on circular turns due to gravity along with restriction of flow direction path on circular directions. Air temperature maximum achieve x= 230 mm is 430K and reduces to 400K because of geometrical configuration increase of radial distance. Figure (10) shows change of inlet nitrous oxide gas from red color to yellow outlet, where as blue to green color in temperature rendering color. Inlet and outlet temperature shown in table 5.ΔT is temperature of outlet air and outlet gas.

$$Ɛ = \frac{T_{inlet\ gas} - T_{outlet\ gas}}{T_{inlet\ gas} - T_{inlet\ air}}$$

$$Ɛ = \frac{1-e^{-NTU(1-R)}}{1-Re^{-NTU(1-R)}} \ ,$$

where $R = \frac{m_{air}\ C_{air}}{m_{nitrous\ gas} C_{nitrous\ gas}}$

TABLE 4: Average Temperature obtained

Temperatures	Helical coil heat exchanger	Cylindrical heat exchanger
$T_{inlet\ gas}$	673 K	673 K
$T_{outlet\ gas}$	570 K	650 K
$T_{inlet\ air}$	300 K	300 K
$T_{outlet\ air}$	430 K	350 K

Thermo electric generator ΔT is proportional to voltage generated and power is directly proportional to voltage; when outlet temperature of nitrous oxide gas and outlet temperature of outlet air taken. Temperature difference is function of power output in seebeck effect. Here shown figure (8) about variation of temperature with respect to each postion linearly increase of HCHE of air because of heat is being transferred from nitrous oxide gas to air as $(C_p)_{air} > (C_p)_{nitrous\ oxide}$. Geometric configuration and gravity plays vital for heat transferred in HCHE is larger than CHE. Temperature fluctuation of nitrous oxide gas in cylindrical heat exchanger (CHE) because of convection mode, flow in opposite direction on each new position will give more heat transition.

6. CONCLUSION

It is found longer the length of CHE and on increasing number coil turns of HCHE, keeping pitch distance and free length of coil constant, increases air outlet temperature and lowers nitrous oxide gas temperature outlet. Effect of conduction between surfaces will be more by decreasing thickness and material thermo physical properties. Further, temperature of outlet gas and inlet air found to be larger by connecting these two points' acts as hot and cold junction for electricity generation measured in terms of watts. Fluctuation in electricity generation practically if gas temperature increase or decrease, but assumption are made for linear gas input. Temperature difference between outlet gas and outlet air in CHE found to 300k but in HCHE 140k on comparison made, so power generation is more in CHE. Complex design of HCHE will produce less electricity by seebeck effect as compared to simple design CHE according to ΔT.

NOMENCLATURE

a	Speed of sound (m/s)
C_p	Specific Heat,(j/kg-k)
C_{air}	Specific heat of air,(j/kg-k)
$C_{nitrous}$	Specific heat of nitrous oxide gas,(j/kg-k)
C_1, C_2, C_{mu}	model constant
$C_{3\varepsilon}$, C_μ	constant that experimentally determined
E	mechanical energy (j/kg)
g	gravitational constant, 9.81 m/s^2.
g_i	gravitational component in i th direction
G_b	generation of turbulent kinetic energy that arises due to buoyancy
G_k	generation of turbulent kinetic energy the arises due to mean velocity
K	Thermal conductivity (W/m-k)
κ	turbulent kinetic energy.
m_{air}	mass flow rate of air (kg/s)
$m_{nitrous}$	mass flow rate of nitrous oxide gas(kg/s)
M_t	Mach number
Pr_t	Prandtl number
NTU	Number of transfer unit
Pr_t	turbulent prandtl number.
Q	heat transfer rate (W)
R	Capacity ratio
$\overline{-\rho u'_i u'_j}$	Reynold stress
T	temperature in Kelvin (K)
u_i, u_j	average velocity components(m/s)
x	defines position in mm
Y_m	fluctuating dilation in compressible turbulence

ABBREVIATIONS

CFD	Computational Fluid Dynamics
CHE	Cylindrical type Heat Exchanger
HCHE	Helical type heat exchanger
UA	Overall heat transfer coefficient

Greek Symbol

β	Coefficient of thermal expansion
Δ	Change in function
ε	dissipation rate
Ɛ	effectiveness of heat exchanger
γ	adiabatic index of air
ρ	density (kg/m^3)
σ_k ,σ_ε	prandtl numbers turbulent kinetic energy and dissipation rate
μ,μ_t	dynamic viscosity, turbulent viscosity (kg /ms)
S_ε ,S_κ	Source term defined by user

Subscript

1,2	number indexes
i,j,1…	indexes
air inlet	air temperature at inlet in Kelvin (K)
air outlet	air temperature at outlet in Kelvin (K)
cylinder	cylindrical heat exchanger
gas inlet	gas temperature at inlet in Kelvin (K)
gas outlet	gas temperature at outlet in Kelvin (K)
helical	helical coil type heat exchanger
lm	logarithmic mean temperature difference
min	minimum

Superscript

‘	fluctuating from mean value

REFERENCES

[1] K. Ikoma, M. Munekiyo, K. Furuya, M. Kobayashi, T.Izumi, and K. Shinnohara, J. Jpn. Inst. Met. 63, 1475(1999).

[2] Tchanche, Bertrand Fankam, et al. "Low-Grade heat conversion into power using small scale organic rankine cycles." *Renewable and Sustainable Energy Reviews*, vol. 15, 2011, pp. 3963–3979., doi:10.12681/eadd/22315.

[3] Li, Shuai, et al. "Optimization of Heat Exchangers with Dimpled Surfaces to Improve the Performance in Thermoelectric Generators Using a Kriging Model." *Journal of Electronic Materials*, vol. 46, no. 5, 2016, pp. 3062–3070., doi:10.1007/s11664-016-5155-4.

[4] Esarte, J, et al. "Modeling heat exchangers for thermoelectric generators." *Journal of Power Source*, vol. 93, 2001, pp. 72–76.

[5] Wang, S.j., et al. "Effect of temperature difference on flow and mixing characteristics of laminar confined opposing jets." *Applied Thermal Engineering*, vol. 26, no. 5-6, 2006, pp. 519–529, doi:10.1016/j.applthermaleng.2005.07.029.

[6] Yiping, Wang, et al. "Numerical Investigation of Power Generation Enhancement for Exhaust Heat Exchanger with Cylindrical Grooves in Thermoelectric Generator Systems." SAE Technical Paper Series, May 2016, doi:10.4271/2016-01-0211.

[7] Y.L. Zhang and M. Cleary, Energy Conversion Management 105, 946 (2015)

[8] M. W. Versteeg, H. K., 3, 3rd ed., ser. 0273738054, 9780273738053.An Introduction to Computational Fluid Dynamics: The Finite Volume Method, 2011, Pearson Education, Limited.

[9] B. E. Launder and D. B. Spalding, Lectures in mathematical models of turbulence, ser. 0124380506 9780124380509. Acad. Pr., 1972.

[10] S. Sarkar and B. Lakshmanan, "Application of a reynolds stress turbulence model to the compressible shear layer," AIAA Journal, vol. 29, no. 5, p.743-749, 1991.

[11] Turbulence modeling for CFD. DCW Industries, 2006.