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Design, analysis and performance evaluation of hybrid exhaust gas heat recovery device to keep food delivery items warm

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ABSTRACT

In the present age of competitive marketing it has become a necessity to deliver good quality and proper condition products from the production facility to the end user, be it industrial goods, fast moving commercial goods or food products. In this area, the rate of online food delivery item is increased very rapidly. The food item which is to be delivered to the customer requires at least 15 to 20 minutes from the time of making. Meanwhile, the food item gets cooled and so as it loses its quality. The present innovation tackles this problem by providing an arrangement which will keep the food item warm up to the time of delivery. The basic principle of working for this arrangement is transferring heat energy of waste exhaust gas, which is any ways going waste to the food chamber which will maintain the food temperature and also reduces the heat from the exhaust. This innovation will be useful mainly for the online food delivery. This can be also used to transfer food from one place to another without losing its quality.

The exhaust gas heat recovery has been done many times earlier with the objective to either generate electricity or direct utilization of heat through direct or indirect heating. The project involves the concept and realization of a hybrid indirect heat transfer via heat pipe mechanism and thermoelectric heater mechanism. The project work embodies the selection process of the insulation box, selection of thermoelectric heater module, thermoelectric energy generator module. Thermal analysis for the several parts of the system is one using Ansys workbench steady-state heat transfer and the experimental evaluation of the performance of the device in individual and combined mode is done by suitable test and trial. The system effectiveness has been calculating and comment on the utilization of further applications has been done.

Keywords: *Hybrid warmer, Online food delivery, Thermoelectric module, Heat pipe.*

1. INTRODUCTION

Nowadays, the food items like Pizza, Burger etc has been ordered online. But to deliver the ordered food item requires the time of about 20-25 minutes. Meanwhile, the food items get cooled and lose its taste. So either customer needs to heat it or to eat as it is. To avoid this loss of food quality, some arrangement should be made which will solve this problem (Rial et al, 2012). If the delivered food is warm then the customer gets more satisfaction and this will attract more customers to order online food which will ultimately increase the business. Keeping this need in mind a device which will solve this problem is to be made. We have two main options either make a more effective insulated box which will restrict the heat transfer or some device which will maintain the temperature of that box at the desired temperature. To make an arrangement which will keep ordered food warm till it reaches the customer. Now the aim is to design an arrangement which will keep the temperature of the box to the required value. All the available boxes only act as an insulation box. There is no such a device which will maintain the temperature of food item until the time of delivery (Ornektekin et al, 1998). With two-wheeler, we are available with the considerably large amount of exhaust gas heat which anyways gets waste. We can utilize this heat from Exhaust Gas to keep food delivery items warm. So the exhaust gas should be circulated around the box and thus temperature can be maintained.

2. PROJECT OVERVIEW

Waste heat is heat, which is generated in a process by way of fuel combustion or chemical reaction, and then “dumped” into the environment even though it could still be reused for some useful and economic purpose. The essential quality of heat is not the amount but rather its “value”. The strategy of how to recover this heat depends in part on the temperature of the waste heat gases and the economics involved. A large quantity of hot flue gases is generated from Boilers, Kilns, Ovens, and Furnaces. If some of this waste heat could be recovered, a considerable amount of primary fuel could be saved. The energy lost in waste gases cannot be fully recovered. However, much of the heat could be recovered and loss minimized by adopting following measures as outlined in this chapter. This will be given an objectives

- Heat load calculation and selection of cabinet with the thermoelectric module to store and transport the food items with a capacity of 4 liters for a temperature gradient of 20 degrees.
- Design selection of heat pipes and the evaporator and condenser fins for maximum heat recovery from the exhaust gases and delivery to the cabinet.
- Design selection of the thermoelectric warmer and analysis of the heat sink used for the Peltier module for the warmer.
- Design selection of the thermoelectric module generator and analysis of the heat sink used for the Peltier module for electricity generation.
- Test and trial on the hybrid system in individual condition and in combine condition to find the effectiveness of the device

3. EXPERIMENTAL SETUP

The solution to the above problem is an innovative concept of utilizing a hybrid system that used heat pipes and thermoelectric warmer to maintain the temperature of the transportation box.

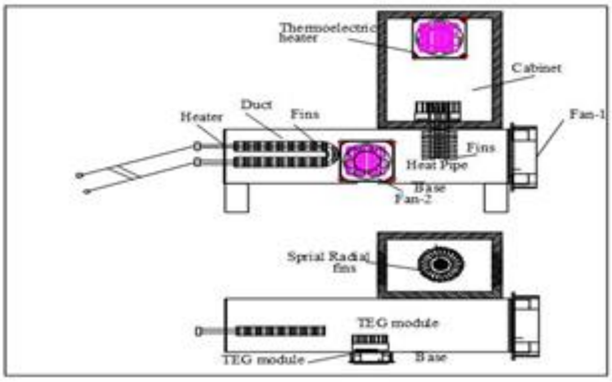


Fig.1 Schematic diagram of the experimental apparatus

3.1 Thermoelectric Warmer

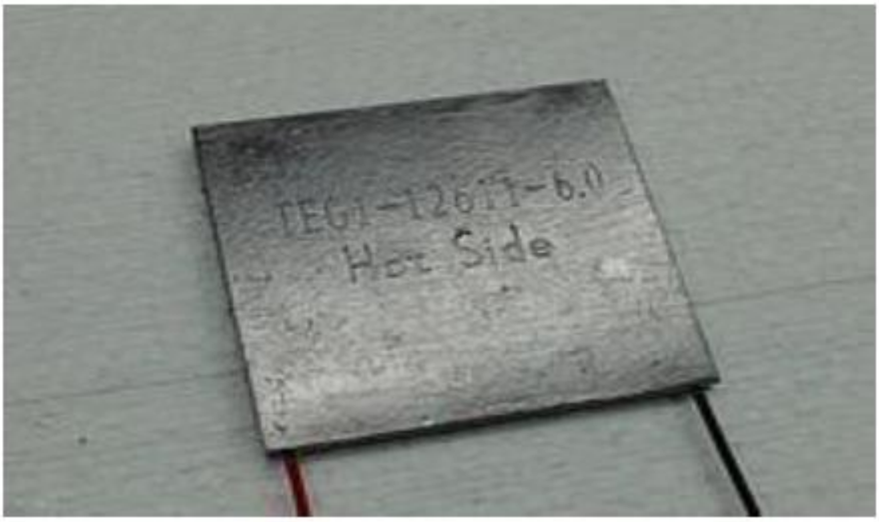


Fig.2 Thermoelectric Effect

Thermoelectric cooling uses the Peltier effect to create a heat flux between the junctions of two different types of materials. A Peltier Warmer, heater or thermoelectric heat pump is a solid-state active heat pump which transfers heat from one side of the device to the other, with consumption of electrical energy, depending on the direction of the current. Such an instrument is also called a Peltier device, Peltier heat pump, solid state refrigerator, or thermoelectric Warmer (TEC). They can be used either for heating or for cooling (refrigeration)[1] although in practice the main application is cooling. It can also be used as a temperature controller that either heats or cools [2]. This technology is far less commonly applied to refrigeration than vapor-compression refrigeration is. The main advantages of a Peltier Warmer (compared to a vapor-compression refrigerator) are its lack of moving parts or circulating a liquid, near-infinite life and invulnerability to potential leaks, and its small size and flexible shape (form factor). Its main disadvantage is high cost and poor power efficiency. Many researchers and companies are trying to develop Peltier Warmers that are both cheap and efficient. (See thermoelectric materials.)

3.2 Thermoelectric Effect

The thermoelectric effect is the direct conversion of temperature differences to electric voltage and vice-versa. A thermoelectric device creates a voltage when there is a different temperature on each side. Conversely, when a voltage is applied to it, it creates a temperature difference. At the atomic scale, an applied temperature gradient causes charge carriers in the material to diffuse from the hot side to the cold side, similar to a classical gas that expands when heated; hence inducing a thermal current. This effect can be used to generate electricity, measure temperature or change the temperature of objects. Because the direction of heating and cooling is determined by the polarity of the applied voltage, thermoelectric devices are efficient temperature controllers.

The term "thermoelectric effect" encompasses three separately identified effects: the Seebeck effect, Peltier effect and Thomson effect. Textbooks may refer to it as the Peltier–Seebeck effect. This separation derives from the independent discoveries of French physicist Jean Charles Athanase Peltier and Estonian-German physicist Thomas Johann Seebeck. Joule heating, the heat that is generated whenever a voltage is applied across a resistive material is related though it is not generally termed a thermoelectric effect. The Peltier– Seebeck and Thomson effects are thermodynamically reversible,[1] whereas Joule heating is not.

3.3 Seebeck Effect

Diagram of the circuit on which Seebeck discovered the Seebeck effect A and B are two different metals. The Seebeck effect is the conversion of temperature differences directly into electricity and is named for German physicist Thomas Johann Seebeck, who, in 1821 discovered that a compass needle would be deflected by a closed loop formed by two metals joined in two places, with a temperature difference between the junctions.

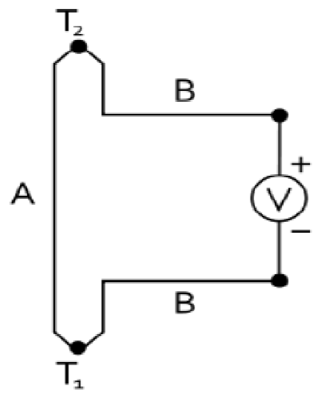


Fig.3 Seebeck Effect

This was because the metals responded differently to the temperature difference, creating a current loop and a magnetic field. Seebeck did not recognize there was an electric current involved, so he called the phenomenon the thermomagnetic effect. Danish physicist Hans Christian Orsted rectified the mistake and coined the term "thermoelectricity". The voltage created by this effect is on the order of several microvolts per kelvin difference. One such combination, copper-constantan, has a Seebeck coefficient of 41 microvolts per Kelvin at room temperature.[2]

The voltage V developed can be derived from:

$$V = \int_{T_1}^{T_2} \left(S_{\mathrm{B}}(T) - S_{\mathrm{A}}(T)\right) dT,$$

Where SA and SB are the thermo powers (Seebeck coefficient) of metals A and B as a function of temperature and T1 and T2 are the temperatures of the two junctions. The Seebeck coefficients are non-linear as a function of temperature and depend on the conductors' absolute temperature, material, and molecular structure. If the Seebeck coefficients are effectively constant for the measured temperature range, the above formula can be approximated as:

$$V = (S_{\mathrm{B}} - S_{\mathrm{A}}) \cdot (T_2 - T_1)$$

The Seebeck effect is used in the thermocouple to measure a temperature difference; absolute temperature may be found by setting one end to a known temperature. A metal of unknown composition can be classified by its thermoelectric effect if a metallic probe of known composition, kept at a constant temperature, is held in contact with it. Industrial quality control instruments use this as thermoelectric alloy sorting to identify metal alloys. Thermocouples in series form a thermopile, sometimes constructed in order to increase the output voltage since the voltage induced over each individual couple is small. Thermoelectric generators are used for creating power from heat differentials and exploit this effect.

3.4 Operating Principle

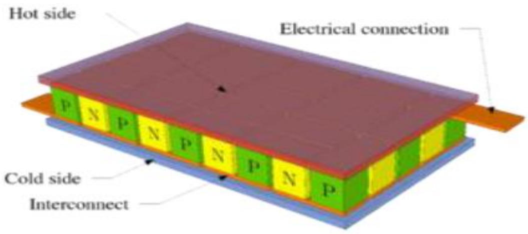


Fig.4 Operating Principle of Peltier Effect

Thermoelectric Warmers operate by the Peltier effect (which also goes by the more general name thermoelectric effect). The device has two sides, and when DC current flows through the device, it brings heat from one side to the other, so that one side gets Warmer while the other gets hotter. The "hot" side is attached to a heat sink so that it remains at ambient temperature, while the cool side goes below room temperature. In some applications, multiple Warmers can be cascaded together for lower temperature.

Experimental procedure

The following Methodology has been used to design and fabricate the Hybrid exhaust gas heat recovery unit to keep food items warm

1) The cabinet space volume is decided to be 4 liter capacity for prototype preparation and the cabinet material is selected accordingly to provide maximum insulation and minimum heat leakage.

2) The selection of heat pipes to trap and transfer heat to the cabinet space from the exhaust gas

3) Selection and analysis of the heat sink modules for the heat pipe evaporator and the condenser section. Modeling will be done using Unigraphics software and the analysis will be done using Ansys software.

4) The selection of thermoelectric module to heat to the cabinet space.

5) Selection and analysis of the heat sink modules for the thermoelectric module section. Modelling will be done using unigraphix software and the analysis will be done using Ansys software.

6) The selection of thermoelectric module to generate electricity from exhaust gases.

7) Selection and analysis of the heat sink modules for the thermoelectric module section. Modeling will be done using unigraphix software and the analysis will be done using Ansys software.

4. DESIGN CALCULATION

Theoretical calculations of the Model box (to be scaled)

Box Design

The box is predesigned as the standard dimensions for the box is defined the manufactures.

Dimensions of box = 17 * 17 *17 inches.

Mass of air inside the box = Volume of the box (V) ×*Density of air (ρ_{air}) … (1)

= 0.4318 * 0.4318 * 0.4318 * 1.02

= 0.0869 Kg

We have, the temperature of pizza at the time of keeping it in the box is about 70 ^{0}C.

So we have to maintain air temperature inside the box about 50^{0}C to 55^{0}C to keep the pizza at that temperature

∴ Heat required to raise the temperature of the air inside the box

= m_a *C_{pa}* ΔT … (2)

= 0.0869 * 1.005 * (55-30)

= 2183.30 Joules

Some of this heat is given by pizza by radiation.

∴ Heat transferred by radiation should be considered

Consider emissivity (ε) of pizza is 0.9.

$Q = \varepsilon * \sigma * A * (T_1^4 - T_2^4)$ … (3)

$= -0.9*8.87*10^{-8}*\frac{\pi}{4}*0.2^2*(70^4-30^4)$

=-8.98W

Pizza radiates 8.98 Joules/sec at the moment when it kept inside the box and the radiation goes on decreasing as its temperature goes on decreasing. At a point where the temperature of pizza and the temperature of the air inside the box will be same then the radiation will be zero.

We have let inside temp of air is 55 ^{0}C.

∴ Heat lost through one wall to the atmosphere

$Q = \frac{dT}{\frac{1}{A*hi}+\frac{x}{A*kfr}+\frac{x}{A*kin}+\frac{1}{A*ho}}$ ….(4)

Now we have h inside for natural convection

So thermal expansion=

$\beta = \frac{1}{T}$ …..(5)

$= \frac{1}{273+55}$

$=3.04878*10^{-3}$ K^{-1}

Grashoff's Number(Gr)= $\frac{(L)^3*g*\beta*\Delta T}{v^2}$

$= \frac{(0.431)^3*9.81*3.0487*10^{-3}*(328-303)}{(18.50*10^{-6})^2}$

$=174.90*10^6$

Now air properties at 55 ^{0}C,

P=1.07 Kg/m^3 , ν=18.50*10^{-6} m^2/sec , Pr= 0.697

$Gr*Pr=0.697*174.90*10^6$

$=1.2191*10^8$

$10^4<Gr*Pr<10^9$ …….For Laminar

$Gr*Pr>10^9$ For Turbulance

Hence the flow is laminar.

From the data book, for Laminar flow,

$H_{inside}=1.42*(\frac{\Delta T}{L})^{0.28}$ ……(6)

H_{inside} =3.91W/m^{2}Ks

Consider while driving the vehicle the air velocity becomes 10 m/sec

Reynolds number= $\frac{\rho*v*L}{\mu}$ ….(7)

Air Properties at 30˚C,

P=1.165Kg/m^3,μ=18.63*10^{6}N-s/m^2, ν=16*10^{-6} m^2/sec,Pr= 0.701, k=0.02675 W/m^{2}K

$Re=\frac{1.165*10*0.431}{18.63*10^{-6}}$

$=2.6957*10^5$

We have criteria,

$Re < 5 * 10^5$ …For Laminar flow

Now taking condition of constant wall temperature

$Nu = 0.332 * Re^{0.5} * Pr^{0.333}$ …(8)

$= 0.332 * (2.6957 * 105)^{0.5} * (0.701)^{0.333}$

= 153.12

$\therefore h = \frac{Nu*k}{x}$ … (9)

$= \frac{153.12*0.02675}{0.431}$

$= 9.503\ W/m^2K$

$Q = \frac{55-30}{\frac{1}{0.431\text{^}2(\frac{1}{3.91}+\frac{0.003}{0.35}+\frac{0.002}{0.04}+\frac{1}{9.503})}}$

= 12.74 W

This is the heat lost per second through the box. After the box air temperature reaches 55 ^{0}C.

Now we have to make up this heat with the help of heat of exhaust gas of delivery vehicle.

Find mass flow rate of exhaust gas.

The velocity of exhaust gas through muffler= 8.13 m/sec

$Area = \frac{\pi}{4} * d_p^2$

$= \frac{\pi}{4} * 0.02^2$

$= 3.14159*10^{-4}\ m^2$

Flow rate = A * V … (10)

$= 3.14159 * 10^{-4} * 8.13$

$= 2.554 * 10^{-3} m^3/sec$

$\therefore mass\ (m) = \rho_g * Q$ … (11)

$= 1.24 * 2.554 * 10^{-3}$

= 0.00316 Kg

C_p of gas = 1090 J/Kg

Heat carried by exhaust gas-

$Q_{eg} = m_{eg} * C_{pg} * \Delta T$

= 0.00316 * 1090 * (120-30)

= 310 W

Now we have to calculate the loss of heat through connecting pipe

Thermal Conductivity of silicon breaded pipe at 100^{0}C is about 0.2 to 0.3W/mK

We have to calculate heat lost through pipe

$Q = \frac{2\pi L \Delta T}{\frac{1}{hi*r1}+\frac{ln\frac{r0}{r1}}{k}+\frac{1}{ho*ro}}$

We have to calculate the inside heat transfer coefficient of pipe h_i.

Thermo-physical properties of exhaust gas at 120^0C,

μ=20.44 * 10^{-6} N-s/m^2, = 25 * 10^{-6} m^2/sec, Pr=0.7, Cp=1009 J/Kgk, K=0.032 W/mk

Re $=\frac{\rho * V * D}{\mu}$

$=\frac{\rho * V * D * A}{\mu * A}$

$=\frac{m * D}{A * \mu}$

$=\frac{4 * 0.00316}{\pi * 0.002 * 20.44 * 10^{\wedge}-6}$

= 9842.06

As Re > 2500, the flow is turbulent

We Have $\frac{L}{D}$=50,Since$\frac{L}{D} \geq 60$

0.7 ≤ Pr ≤160, for heating n=0.4

$\therefore$ Nu = 0.023 × (Re) $^{0.8}$ × (Pr) $^{0.4}$ … (12)

= 0.023 × $(9842.06)^{0.8}$ × $0.7^{0.4}$

Nu =31.2058

$h_i = \frac{Nu * k}{D}$

$=\frac{31.20 * 0.032}{0.02}$

=49.92 W/m^2K

Now we have to calculate outside heat transfer coefficient of tube

Considering the air velocity while vehicle is 10 m/s

We have air properties at 30^0C

ρ = 1.165 Kg/m^3,μ =18.63 * 10^{-6} N-s/m^2, ν= 16 * $10^{-6}$$m^2$/s, Pr = 0.701,

k = 0.02675 W/mK

Re $=\frac{V * D}{\nu}$ … (13)

$=\frac{10 * 0.02}{16 * 10^{\wedge}-6}$

= 12500

From heat transfer data book,

For wall temperature of 70^0C, Pr for wall =0.694, Re=12500, C = 0.26, m = 0.6, n= 0.37

Nu = C *Re^m*Pr^n* $\left(\frac{Pr^{\wedge}\infty}{Prw}\right)^{0.25}$ … (14)

= 0.26 * 125000.6 * 0.70.37 * $\left(\frac{.701}{.694}\right)^{0.25}$

= 65.59

Now,

$h_o = \frac{K}{D} * Nu$

$=\frac{0.2675*65.59}{.02}$

$=87.72 W/m^2 K$

$Q=\frac{2\pi L\Delta T}{\frac{1}{hi*r1}+\frac{ln\frac{r0}{r1}}{k}+\frac{1}{ho*ro}}$

$=\frac{2\pi*1*(120-30)}{\frac{1}{49.92*0.01}+\frac{1}{0.2}*\left(\frac{0.012}{0.01}\right)+\frac{1}{87.72*0.812}}$

=146.41W

Now, we will provide insulation thickness of 7 mm,

Heat loss $=\frac{2\pi L\Delta T}{\frac{1}{hi*r1}+\frac{ln\frac{r0}{r1}}{k}+\frac{1}{ho*ro}}$

$=\frac{565.48}{2+.9116+17.67+0.599}$

=26.69W

Thus total heat is given to the box at entry = 309.99 – 26.69

= 283.3 W

Now we have,

The temperature of exhaust gas at the entry of the delivery box,

$Q = m_{eg} *C_{pg} *\Delta T$

$2833 =0.00316 * 1090 * (T_g – 30)$

$T_g= 112.24^0C$

Velocity at the entry of pipe by measurement = 5.2 m/sec

Assumptions-

- Velocity remains constant from entry to exit of the delivery box.
- The temperature of gas remains constant through the chamber.

Now,

Reynolds number $=\frac{\rho*V*L}{\mu}$

We have gas properties at 71^0C,

$\rho = 0.950\ Kg/m^3$, $\mu =2 * 10^{-6}\ N\text{-}s/m^2$, $\nu = 21.54 * 10^{-6}\ m^2/s$, Pr = 0.690,

k = 0.03128 W/mK

$Re =\frac{.950*5.2*0.431}{20.38*10-6}$

$= 1.044*10^5$

For wall, $Re < 5 * 10^5$ … Laminar Flow

Taking condition of constant wall temperature,

$Nu = 0.332 * Re^{0.5} * Pr^{0.333}$

$= 0.332 (1.044 * 10^5)^{0.5}* 0.69^{0.333}$

= 94.83

$h =\frac{Nu*k}{D}$

h =$\frac{0.03128*94.83}{.431}$

h =6.8823w/m^{2}K

Inside box air will have free convection, air temperature = 30^{0}C

Assume the plate temperature about 80^{0}C for calculation.

Mean film thickness =$\frac{30+80}{2}$

=55˚C

=328K

Properties of air at 55^{0}C,

ρ = 1.07 Kg/m^3,μ = 10^{-6} N-s/m^2, ν= 18.50 * 10^{-6} m^2/s, Pr = 0.697,

k = 0.02856 W/mK

β =$\frac{1}{T}$

=$\frac{1}{328}$

= 3.0487 * 10^{-3} K^{-1}

GrashoffsNumber =$\frac{x3*g*\beta*(Ts-T\infty)}{\nu 2}$

= $\frac{.431^3*9.81*3.0487*10^{-3}*(80-30)}{(18.50*10^{-6})^{\wedge}2}$

=3.4973 * 10^8

Gr * Pr = 0.697 * 3.4973 * 10^8

= 2.4376 * 10^8

We have condition, Gr *Pr< 10^9 … For Laminar flow

Hence for Laminar flow and constant wall temperature,

Nux = 0.508 * Pr$^{0.5}$ * Gr$^{0.25}$ … (15)

=0.508 * (0.697)$^{0.5}$* (3.497 * 108)$^{0.25}$

Nux= 51.17

h =$\frac{Nu*K}{L}$

= 3.39 W/m^{3}K

Determine the thickness of the copper sheet.

Total heat required to = Heat lost from Box + Heat required to raise the temperature to 55^{0}C

add by exhaust gas

Consider a time interval of 15 min to attain the temperature of 55^{0}C

∴ Heat rate required =$\frac{2183}{15*60}$

= 2.425 W

Total heat required = 8.98 + 2.425

= 11.40 W

∴Thickness of plate

$Q=\frac{A*dT}{\frac{1}{hi}+\frac{x}{ka}+\frac{1}{ho}}$

x = 0.00125 m

x = 1.25 mm

Thus the plate of thickness 1.25mm is to be selected.

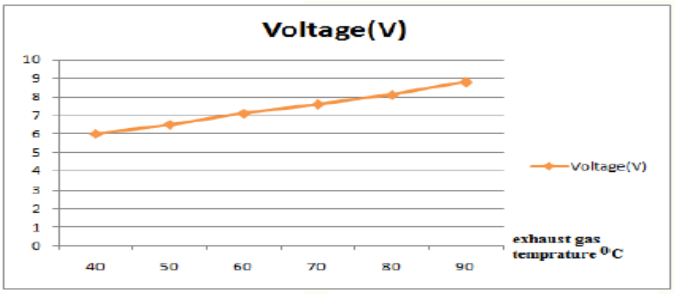
5. RESULT ANALYSIS

5.1 Test-1 Thermoelectric Generator Module Test

Observation Table

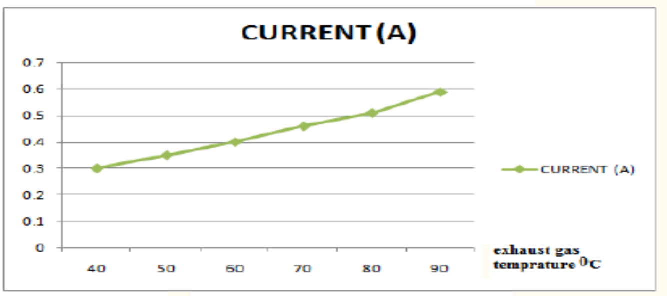
Tempera true	ΔT(a is)	VOLTA GE	CURRE NT A	POW ER watt
40	10	6	0.300	1.8
50	20	6.5	0.350	2.275
60	30	7.1	0.400	2.84
70	40	7.6	0.460	3.496
80	50	8.1	0.510	4.131
90	60	8.8	0.590	5.192

5.1.1 Graph of Voltage generated Vs Temperature of exhaust gas



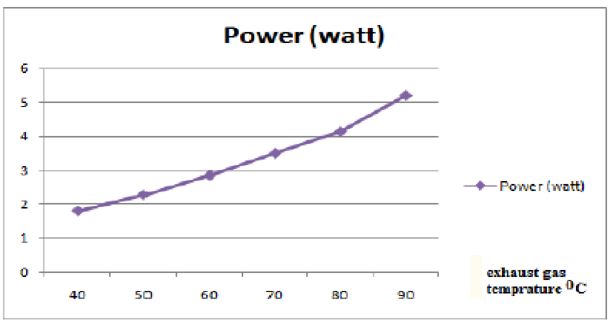
The graph shows that with an increase in temperature of exhaust gas the voltage from the TEG module increases.

5.1.2 Graph of Current generated Vs Temperature of exhaust gas



The graph shows that with an increase in temperature of exhaust gas the current from the TEG module increases.

5.1.3 Graph of Power generated Vs Temperature of exhaust gas



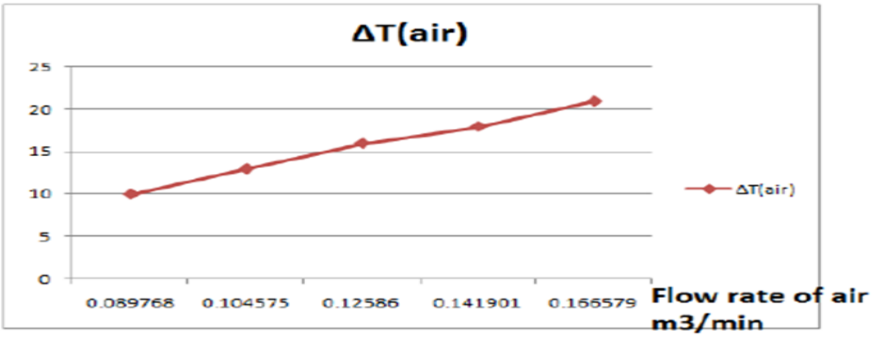
The graph shows that with an increase in temperature of exhaust gas the power from the TEG module increases.

5.2 Test-2 Test of The Heat Pipe Module

Observation Table

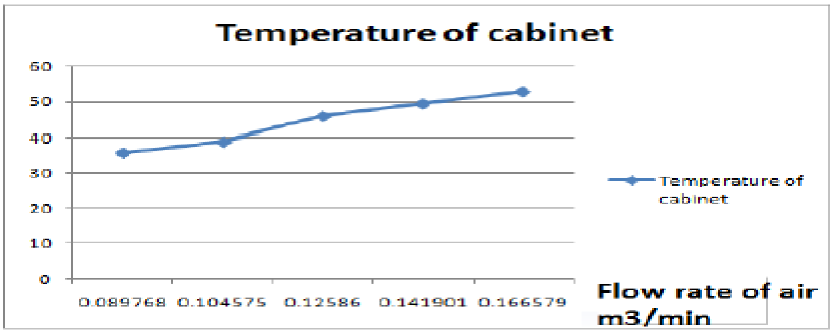
Flow rate of air	ΔT(air)	Temperature of cabinet
0.089768	10	36
0.104575	13	39
0.12586	16	46
0.141901	18	49.5
0.166579	21	53

5.2.1 Graph of Temperature Gradient of Exhaust Gas Vs Flow rate of air



The graph indicates that the flow rate the temperature gradient of the exhaust gas increases indicating that heat pipe system works effectively.

5.2.2 Graph of Cabinet Temperature Vs Flow rate of air



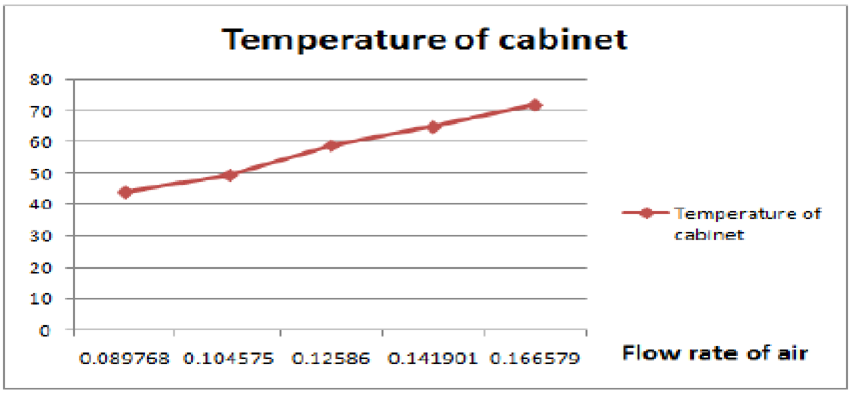
The graph indicates that as the flow rate increases the temperature of the cabinet increases indicating that heat pipe system works effectively in transferring the exhaust gas to the cabinet.

5.3 Test-3 Test on the Hybrid system

Observation Table

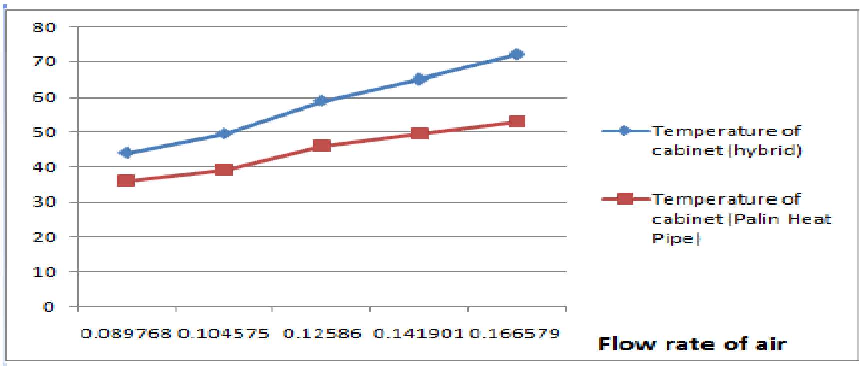
Flow rate of air	Temperature of cabinet	Effectiveness
0.089768	44	1.222
0.104575	49.5	1.269
0.12586	*59*	1.283
0.141901	65	1.313
0.166579	72	1.358

5.3.1 Graph of Cabinet Temperature Vs. The flow rate of air



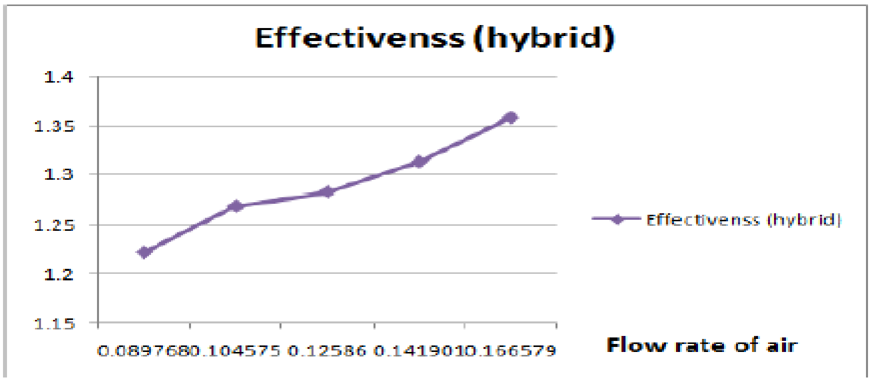
The graph indicates that as the flow rate increases the temperature of the cabinet increases indicating that heat pipe system works effectively in transferring the exhaust gas to the cabinet

5.3.2 Comparison Graph of Hybrid system with Plain Heat Pipe system



The comparison shows that the Hybrid system performs better than the plain heat pipe system.

5.3.3 Graph of Effectiveness of the Hybrid system Vs. Flow rate of Air



The graph shows that the effectiveness of the system increases with a flow rate of air.

6. CONCLUSIONS

1) The insulation Cabined was developed using the appropriate selection process and thereby minimum heat loss was achieved.

2) Heat pipe system was developed by suitable selecting 8 mm heat pipes, 2 No's for effective heat trap from exhaust gases.

3) Spiral radial fins appropriately selected and designed and analysis revealed that close to 90-watt power capacity of the sink ensures that maximum heat will be transferred from the exhaust gases to the cabinet.

4) The appropriate selection of the thermoelectric generator enabled to derive energy from exhaust gases which was close to 5 watt, considering that 30 % load is shared by the thermoelectric warmer the i.e. 9 watts is required to run the so, the TEG module developed more than 50% of the load thereby increasing the effectiveness of the system as a hole.

5) The Hybrid system is better in performance than the plain heat pipe system

6) The hybrid system is close to 1.35 time effective than the plain heat pipe system.

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