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SYSTEM DESIGN OF A HIGH-SPEED E-TURBINE SYSTEM FOR WASTE HEAT RECOVERY IN AUTOMOTIVE VEHICLES

Muhammad Ishaq Khan
Department of Thermal Energy Engineering
NUST H-12, Islamabad Pakistan
madishaq143@gmail.com

Adeel Javed
Department of Thermal Energy Engineering
NUST H-12, Islamabad Pakistan
adeeljaved@uspcase.nust.edu.pk

Abstract

Due to the rapid industrialization and urbanization of Pakistan, automotive transport sector is one of the fastest growing sectors in Pakistan in terms of output, energy consumption and CO2 emissions. The existing automotive sector in Pakistan, hardly complying to an obsolete Euro II emissions standards, requires a sizable enhancement in energy conversion efficiency. Furthermore, there are two parasitic loads on conventional IC Engine, (1) generate current to recharge the vehicle's battery, The electrical charge is produced by the alternator (generator) that is commonly coupled to the crankshaft pulley of the IC engine through a belt-drive system. (2) The air-conditioning compressor draws several kilowatts of power from the IC engine at peak load, thereby increasing the fuel consumption of the vehicle considerably. On average the air-conditioning system can increase the fuel consumption of a vehicle by 20% . Internal combustion engine wastes a lot of energy through their exhaust. Different IC Engines(660cm^3,1000cm^3,1300cm^3) have been modeled in MATLAB. Results showed that on average the exhaust gas temperature ranges from 850K to 1100K at the engines operating at full load. The mass flow rate of exhaust gases also increases with the engine rpm. The pressure of the exhaust gases is in the range 4-6 bar. This exhaust energy is recovered by an e-turbine system. E-turbine system consists of turbine, generator and spindle. Exhaust energy rotates the turbine placed in the exhaust manifold which in turns turn the shaft. Shaft is placed in the generator and due to EMF , current is produced. The e-turbine system produce power that is almost sufficient to run the vehicle HVAC compressor, replacing the engine parasitic load

Keywords: Electric Turbine, Internal Combustion Engine, HVAC, MATLAB, Alternator

1. INTRODUCTION

The inadequate accessibility and huge dependency on the fossil fuel due to the recent developments in industrial technologies shifted the attention of research towards the effective and efficient use of energy. Most part of fossil fuels around the world is used by the internal combustion engines. The technological development and a good power to weight ratio made the IC engine to be the best option for transportation, power plants and agriculture etc.[1].

IC engines are most widely used in the field of transportation and mobile power generation purposes [2]. But IC engines waste a reasonable amount of its fuel energy to the environment. Only 30-40% of its fuel energy is converted into useful mechanical work [3]. A huge amount of fuel energy is wasted to the environment in the form of exhaust gases, through the coolant and charge air[2].

In recent years, due to increasing prices and shortage of fossil fuel compel the researchers and engineers to think about an engine design that would use the fuel and produce the work output in an efficient way and with a small and clean waste. They have developed certain methods that reduce emission but still the waste energy is in reasonable amount i-e. supercharge, lean mixture etc. Major portion of waste heat from the engine is in the form of exhaust gases. The engineers and researchers tried to recover this exhaust energy. Various waste heat recovery technologies are developed.

Waste heat recovery technologies have a great potential to increase the overall efficiency of engine and is a hot topic for research [4], [5]. Combustion inside the engine and its emissions have been improved by the turbocharger technology [6], [7]. The turbocharger is now a technologically mature system for waste heat recovery application. Turbocharger is primarily a turbine-driven compressor and remains largely associated with internal combustion (IC) engines. Compared to a non-turbocharged IC engine delivering similar magnitude of power, a turbocharged IC engine will be smaller, lighter, and more efficient [10]. The exhaust gas energy that would have otherwise been wasted is used to drive the turbine, which then transmits the shaft power to the compressor. One of the waste heat recovery technologies is turbocompounding the engine. Low pressure turbine is placed after the high pressure turbocharger compressor. The power produced by the LP turbine is transferred to wheels by coupling it with the engine crankshaft. The main disadvantage of turbocompound engine is its high pumping loses. Engine needs to do more work in the exhaust stroke to throw out exhaust gases from the cylinder [8]. Another method of turbocompounding which is also used for waste heat recovery is electric turbocompounding. ET converts the LP turbine shaft work into electric power by using a high speed generator [9]. Another promising technology for WHR that has been developed nowadays is thermoelectric generator. The working principle behind this technology is seebeck effect. Two different materials are placed in the path of exhaust gases. Electric power is produced due to the flow of energy by virtue of temperature difference of exhaust gases and the external environment. But the low efficiency of this system is the main hurdle in the implementation [9]. Waste heat is also being recovered by using different thermodynamic cycles such as Stirling cycle, Brayton cycle, Kalina cycle, and Rankine cycle [2]. Organic Rankine cycle is the most promising cycle among the above thermodynamic cycles due to its many advantages i-e flexibility, simple design and easy maintenance.

The transport sector, one of the important sectors of Pakistan's economy, contributes around 10 percent to the GDP and 6 percent employment to the country [11]. Oil and Gas is the most consumed source of energy in transport. The petroleum consumption in the sector reaches 10 million TOE (Tons of Oil Equivalent) in 2013, registering a growth rate of 1.8 percent in the last decade [12]. The number of vehicles, mostly using petroleum products and natural gas, have increased rapidly from 2.7 million vehicles in 1990 to 9.8 million in 2010, thereby contributing worryingly to air quality degradation in Pakistan. The existing automotive sector in Pakistan, hardly complying to an obsolete Euro II emissions standards, requires a sizable enhancement in energy conversion efficiency. Also in Pakistan, most of the automotive vehicles are equipped with naturally aspirated engine(non-turbocharged). So the exhaust waste heat is more as compared to the turbocharged engine. In conventional automotive vehicles, there are two parasitic loads on the engine. 1) vehicle's battery charging system. The electrical charge is produced by the alternator (generator) that is commonly coupled to the crankshaft pulley of the IC engine through a belt-drive system. 2) vehicle's HVAC system. . The HVAC system is also an integral automotive system, which ensures the thermal comfort of the passengers and responsible for the circulation of clean air in the passenger cabin. The air-conditioning compressor draws several kilowatts of power from the IC engine at peak load, thereby increasing the fuel consumption of the vehicle considerably. On average the air-conditioning system can increase the fuel consumption of a vehicle by 20% [13]. The vehicle's

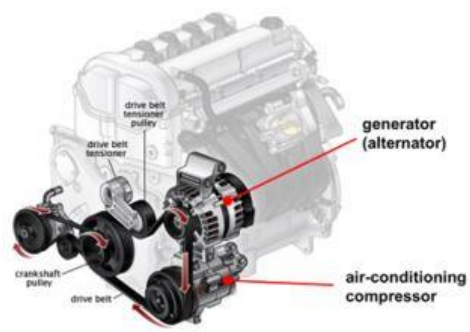

Figure 1: conventional automotive engine

performance is also influenced negatively. The HVAC load on the engine is substantial for vehicles operating in the regions with hot climate conditions. In Pakistan, the summer season is of the duration of 7-9 months. So for a thermal comfort, the use of air conditioners in the car cabin is necessary and a lot of engine power is used to run the AC compressor. On one side, a huge of amount energy is wasted through the exhaust and on the other side, these parasitic loads are responsible for the high fuel consumption. This paper proposes a system that is used to recover this waste heat and replaces these parasitic loads improving fuel consumption of the vehicles in Pakistan. The

E-Turbine concept is a novel and innovative idea for the recovery of automotive waste heat. This technology is best suitable for conventional automotive vehicles. The E-Turbine system consist of turbine, spindle and generator. the working principle of e-turbine system is that exhaust gases pass through the turbine that is placed in the exhaust manifold of engine. Turbine extract power from the exhaust that will otherwise be wasted. Turbine shaft rotates, upon which an electric generator is mounted. Due to change in EMF, generator produced electricity. This electrical power is used for the operation of HVAC compressor and for battery charging which is used to run other electrical accessories of the vehicle. this technology replaces the two parasitic loads that are discussed above and also recover the waste heat in a simple way.

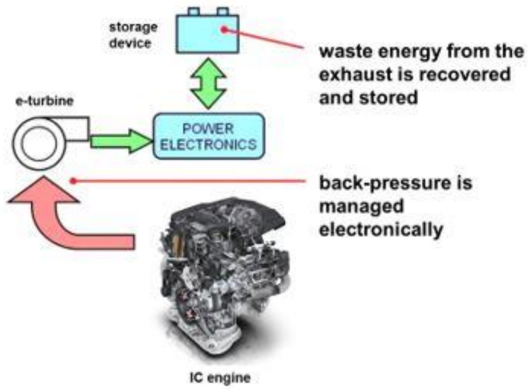

Figure 2:Illustration of E-Turbine concept

2. Methodology

The main step in the designing of E-Turbine system is modeling of different IC Engines that are currently used in Pakistan's transport sector. 660cm^3, 1000cm^3, 1300cm^3 IC engines are modelled in MATLAB. Zero-dimensional model is used for the modelling of these IC engine in MATLAB. Model is verified by modelling 1.4L engine and its results are compared with the published data[14].

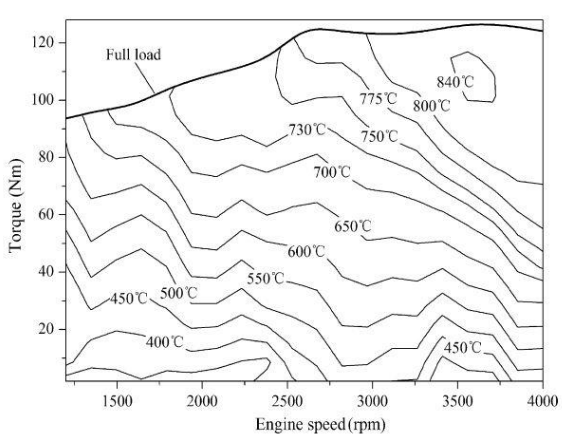

Figure 3: variation of torque, temperature with rpm

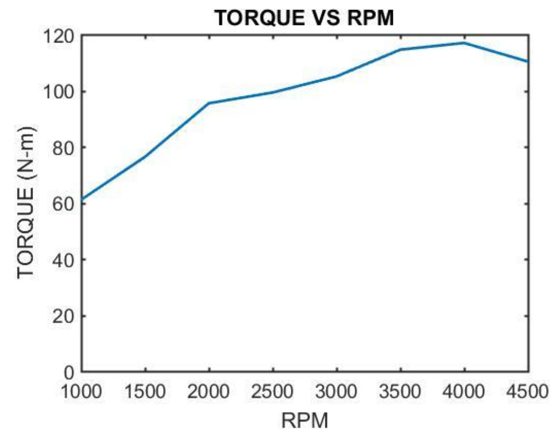

Figure 4: MATLAB Model results

First In-cylinder pressure, temperature and indicated work are calculated by the model.

For pressure calculation, the equation used is

$$\frac{dP}{d\theta} = -\gamma \frac{PdV}{Vd\theta} + \frac{(\gamma-1)}{V}\frac{dQ}{d\theta} - \frac{\gamma \dot{m}_1}{\omega m} P \qquad (1)$$

$$C = \frac{\dot{m}_1}{m}$$

For temperature calculation, the equation used is

$$\frac{1}{P}\frac{dP}{d\theta} + \frac{1}{V}\frac{dV}{d\theta} = \frac{1}{m}\frac{dm}{d\theta} + \frac{1}{T}\frac{dT}{d\theta} \qquad (2)$$

$$\frac{dm}{d\theta} = -\frac{\dot{m}_1}{\omega}$$

For indicated work, the equation used is

$$\frac{dW}{d\theta} = P\frac{dV}{d\theta} \qquad (3)$$

After calculating this, brake power, torque, mass flow rate of exhaust gases, exhaust energy and availability are calculated at different rotational speeds for the stated engines.

The equations used are,

For brake power,

$$W_b = \frac{n_c W_i rps}{2} \eta_m \qquad (4)$$

For torque,

$$\dot{W}_b = 2\pi\tau \; rps \qquad (5)$$

For mass flow rate of exhaust gases,

$$\eta_o = \frac{P}{q_c \dot{m}_f} \qquad (6)$$

$$\dot{m}_a = \dot{m}_f \times AFR$$

$$\dot{m}_{exh} = \dot{m}_a + \dot{m}_f$$

For exhaust energy,

$$\dot{Q}_{exh} = \dot{m}_{exh} \times C_{pexh} \times \Delta T \qquad (7)$$

For availability,

$$A_{exh} = Q_{exh} + \frac{(m_f \times m_a) T_{amb} (C_{pexh} \times Ln\left(\frac{T_{amb}}{T_{exh}}\right) - R_{exh} \times Ln\left(\frac{P_{amb}}{P_{exh}}\right))}{3600}$$

Final step is the selection of turbine from the Ns, Ds diagram. The turbine is selected on the basis of available energy and exhaust mass flow rate from the Ns, Ds diagram.

The equations used are,

$$n_s = N\left(\frac{\dot{m}}{\rho_e}\right)^{\frac{1}{2}} \times (\Delta h_{0s})^{\frac{-3}{4}} \qquad (9)$$

$$\Delta h_{0s} = C_p T_{01}[1 - (p_{02}/p_{01})^{(\gamma-1)/\gamma}]$$

$$D_s = \frac{D\left(\frac{\Delta p}{\rho}\right)^{\frac{1}{4}}}{Q^{\frac{1}{2}}} \qquad (10)$$

3. Results and Discussion

Engine 660cm³

Engine R06A having a displacement volume of 660cm³ has been modelled in MATLAB. Brake power, mass flow rate of exhaust gases and exhaust energy are plotted against different rpm. Brake power increases with the rpm, reaches its maximum and then decreases. This is due to the fact that frictional loses increases at the higher rpms, so the mechanical efficiency decreases and ultimately power drops. The temperature of the exhaust gases also increases with the rpm at peak load. Exhaust energy and its mass flow rate increase with the rpm. The results are shown in the figure 5 below,

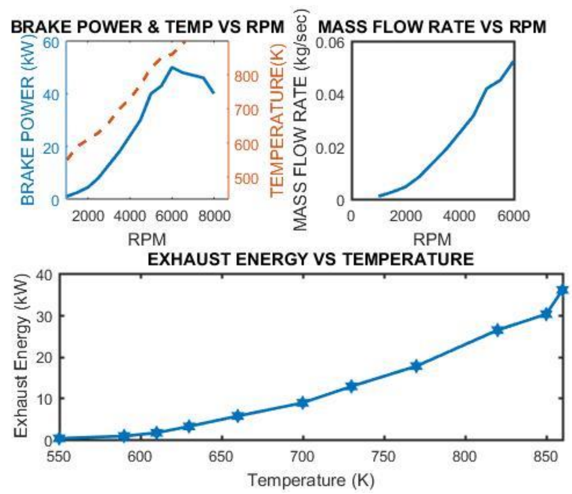

Figure 5: Results of R06A (660cm³)

Engine 1000cm³

Engine K10B having a displacement volume of 1000cm³ has been modelled in MATLAB to calculate its brake power, torque, exhaust energy, mass flow rate of exhaust gases at different rpm. The graphs shows that maximum power and maximum torque occur at two different rpms. Maximum torque occurs at low rpm while maximum power occurs at high rpm. The exhaust energy, its mass flow rate, and temperature of exhaust gases increases with the rpm at peak load.

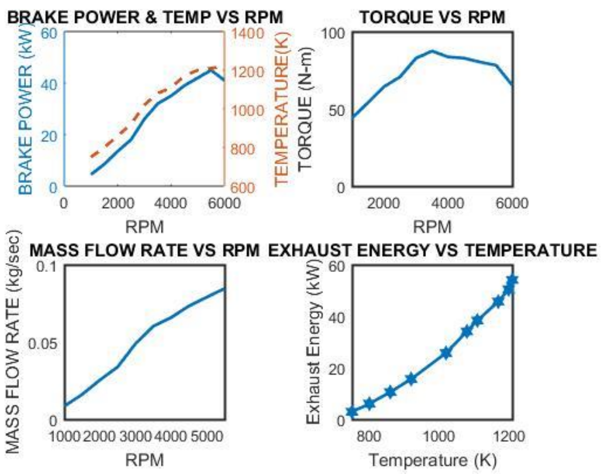

Figure 6: Results of K10B(1000cm^3)

Engine 1300cm^3

Engine 2NZ-FE having a displacement volume of 1300cm^3 has been modelled in MATLAB to calculate its brake power, torque, exhaust energy, mass flow rate of exhaust energy at different rpm. The exhaust energy, its mass flow rate and temperature increase with rpm at peak load.

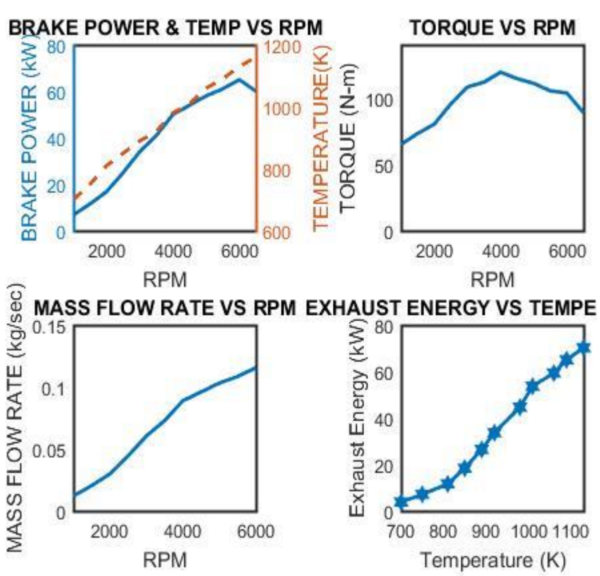

Figure 7: Results of 2NZ-FE (1300cm^3)

Availability Analysis

The exhaust energy that is wasted in the exhaust gases is not completely recoverable. Some portion of exhaust energy should be thrown out to the environment. The available useful energy present in exhaust gases that can be converted into useful work is called exergy. This available energy is less than the total energy present in the exhaust gases. Exergy analysis has been done for the stated engines at different rpm at peak load. The table shows the exhaust energy and exergy for engines at different rpm.

Table 1; Exergy/Available energy at different rpm of 660cm^3

Rpm	Exhaust Energy (kW)	Exergy (kW)
1000	1.03	0.5438
2000	1.6146	1.31
3000	5.66	3.79
4000	12.80	8.56
5000	26.35	18.13
6000	36.02	25.76

Table 2;Exergy/Available energy at different rpm of 1000cm^3

Rpm	Exhaust Energy (kW)	Exergy (kW)
1000	2.8	1.53
2000	10.55	5.297
3000	25.69	13.64
4000	38.31	20.425
5000	50.4	27.88
5500	54.07	30.31

Table 3;Exergy/Available energy at different rpm of 1300cm^3

Rpm	Exhaust Energy (kW)	Exergy (kW)
1000	3.822	2.04
2000	11.62	5.76
3000	26.462	13.24
4000	44.64	24.73
5000	59.35	34.16
6000	70.227	41.17

AC Compressor Power

In Pakistan, Sanden AC compressor are widely used in automotive vehicles. SD7H15 has been selected for study to find out that how much power it consume from the engine at its maximum refrigerating capacity. The chart shows that at its maximum refrigerating capacity, it draws almost 5kW from the engine.

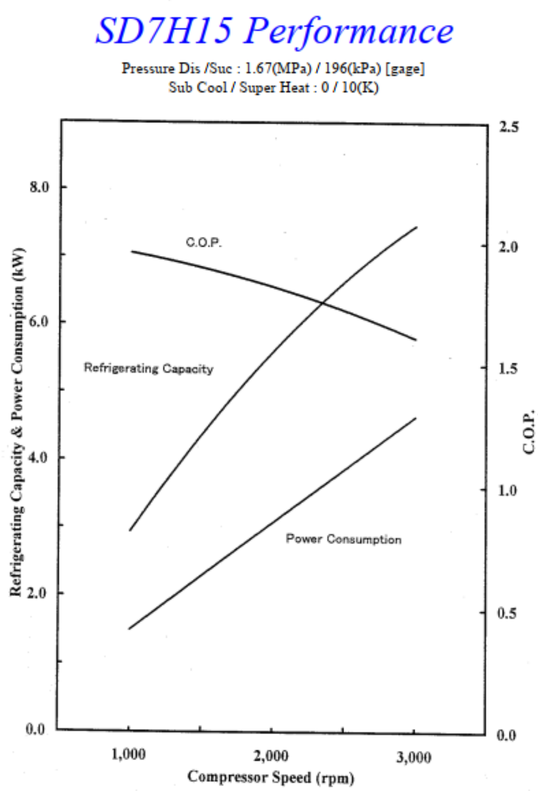

Figure 8: Compressor performance map

Turbine selection

Engine 1000cm3 is selected for which the turbine is designed. The design point is selected at 3000 rpm. Available energy at 3000 rpm is 13.64kW and the power needs to run the compressor is 5 kW. By using the above equations, the selection of radial turbine is made producing 5.5kW power. This power is enough to run the AC compressor of the vehicle at its maximum refrigerating capacity.

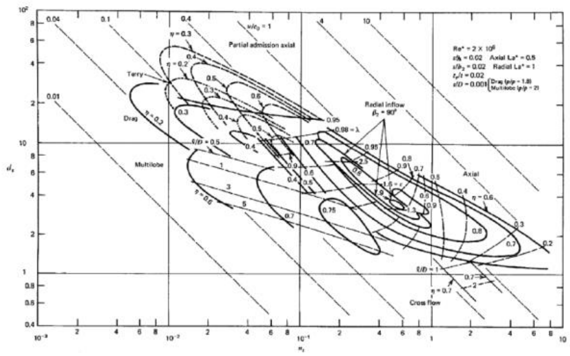

Figure 9: Ns, Ds diagram for turbomachinery selection

4. CONCLUSIONS

AC compressor load on engine is replaced by the E-Turbine system which improves the fuel consumption of the vehicle. The removal of AC compressor load from the engine also improves the pick of the vehicle. This paper gives the conceptual design of the E-Turbine system. This idea needs to be commercialized for the improved results.

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Zhijun Peng , Tianyou Wang , Yongling He , Xiaoyi Yang Lipeng Lu