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The Thermodynamic Study of Turbocharger Pressure Ratio and Ambient Temperature Variation on Exergy Destruction Estimation of Homogeneous Charge Compression Ignition Engine Cogeneration System

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Abstract - **Homogeneous Charge Compression Ignition (HCCI) technology is different from conventional combustion technologies. It has the combination of lean and premixed fuel air mixture and charge is compression ignited so it has multiple ignition points throughout the combustion chamber thus eliminating the high peak temperature inside the combustion chamber. This new engine technology is helpful in production of ultra low NO_x and particulate emissions. The use of lean and unthrottled operation yields higher efficiency and better fuel economy also. In this paper, a new HCCI engine combined cycle cogeneration system is proposed and studied. The system is equipped with turbocharger, fuel vaporizer, engine, catalytic converter, different components of Organic Rankine cycle (ORC) and further heat recovery steam generator (HRSG) for waste heat utilization from the exhaust gases to obtain process heat. An exergy analysis is applied to the different components of HCCI engine cogeneration system to examine the thermodynamic losses in terms of exergy destruction and the effect of ambient temperature and turbocharger pressure ratio is obtained. The result shows a ranking among the components of the system on the basis of thermodynamic losses or the exergy destruction. This paper shows how an exergy method can yield effect of ambient conditions and design parameters values to reduce losses in various components of HCCI engine cogeneration system.**

Keywords: **Cogeneration, Exergy analysis, Exergy destruction, HCCI engine, Wet ethanol**

I. INTRODUCTION

IC Engines have played a key role, both socially and economically, in shaping the modern world. However in recent decades, serious concerns have been raised with regard to the environmental impact of exhaust and particulate emission arising from operation of these engines. In addition, concerns about world's finite oil reserves have lead to rising fuel prices. These two factors lead to massive pressure on vehicle manufacturer for Research and development (R&D) to produce ever cleaner and more efficient vehicles. R&D efforts always focus on improving engine efficiency while meeting future national and state emissions regulations through a combination of combustion technologies that minimize in-cylinder formation of emissions. In an effort to combine the benefits of both SI and CI engines, homogeneous charge compression ignition (HCCI) engines are being developed. The start of ignition in HCCI engines is not directly initiated by an external event such as the firing of a spark plug in SI engines or the beginning of fuel injection in standard diesel engines; instead HCCI relies solely on the fuel auto ignition process to control the combustion [1].

II. RECENT AUTOMOTIVE TECHNOLOGIES

The ultimate intention of emission legislation to drive technologies to the position where realistic reasonably priced in close proximity to zero emission with satisfactory performance becomes a reality. Recent progresses in conventional SI and CI engine technology have allowed huge improvement in emission and fuel consumption. The adoption of three way catalytic converter in SI gasoline engine has considerably reduced the emission of carbon monoxide (CO), unburned hydrocarbon (HC), and oxides of nitrogen (NO_x). High speed direct injection (HSDI) diesel engines and stratified charge gasoline direct injection (GDI) engines permit lean combustion by managing fuel flow rate. Therefore these approaches achieve significant reduction in fuel consumption. Alternative Technologies such as fuel cells and electric vehicles that have been introduced in the market come with associated problems. These include high cost, changes required to the fuelling infrastructure and lack of development to support these technologies.

An alternative combustion technology commonly known as homogeneous charge compression ignition has emerged and it has the potential to achieve high efficiency and very negligible NO_X and virtually no smoke emissions. It has the abilities to meet current and future emission legislation, without the need for expensive exhaust gas treatment systems. In fact HCCI combustion is a new combustion process in reciprocating internal combustion engines. In 1979, the most recognized original work in lean combustion process for IC engine i.e. HCCI was reported by Onishi et al [2]. They discussed HCCI combustion and called it active thermo atmospheric combustion (ATAC). They applied it on 2 stroke gasoline engine with lean mixture at part load operation and consequently achieved improved fuel economy and reduced exhaust emissions along with lower noise and vibration. Noguchi et al (1979) [3] Studied a gasoline engine combustion by observation of intermediate reactive products during combustion. They observed that the air fuel mixture burns in the reaction zone with flame front as it propagates across the combustion chamber and it has a clear separation between burned charge and unburned charge where as in the case of homogeneous charge compression ignition (HCCI) engine, all the charge is consumed simultaneously as the charge auto ignites and it has multiple ignition points. However this combustion process is at a lower rate. These works were motivated by their desire to control the irregular combustion caused by auto ignition of cylinder charge to obtain stable lean burn combustion of 2- stroke gasoline engines. Thring R.H. (1989) [1] introduced the terminology homogeneous charge compression ignition (HCCI) for this type of combustion process and it was further adopted by many researcher of present time to describe such combustion process in both gasoline and diesel engine. He suggested that the passenger car engine can run on HCCI mode at idle and light load operation to obtain fuel economy and smooth operation while switching to conventional gasoline engine operation at full power for good specific power output. Olsson and Johnsson (2001) [4] used a modified 12 liter six cylinder, turbo diesel engine mainly used in truck application for study of HCCI engine. They achieved HCCI combustion over a large speed and load range by employing combination of isooctane and heptane through a close loop control, as well as turbo charging, high compression ratio and intake air heating. The technology of HCCI is attractive as there is no need for huge modifications to the existing hardware of IC engines and its fuelling system and it further considerably reduces NOx emissions.

A. Ethanol in HCCI Engine

Recently a lot of research is being carried out for the use of alternate fuels in HCCI engine. Mach et al (2009) [5] investigated 4-cylinder 1.9 liter engine running in HCCI mode fuelled with wet ethanol. They investigated the effect of ethanol water fraction on the engine's operating limits, exhaust emission, intake temperature and heat release rates. Saisirirat et al (2011) [6] investigated the auto ignition and combustion characteristics in HCCI using ethanol/n-heptane mixture with varying alcohol percentage up to 57% by volume. Diesel engine fuelled with alcohol/n-heptane blend was used at constant equivalence ratio of 0.3, with intake temperature at 80^0C operating at 1500 rpm. Wu et al (2011) [7] investigated the reduction in smoke and NO_X of a partial HCCI engine using premixed gasoline and ethanol as a fuel. The experiments were conducted under different engine speed of 1200, 1500 and 1800 rpm and at different loads. The result shows the successful operation of HCCI engine with ethanol resulting good efficiency and effectively reduced emissions.

Exergy analysis of wet ethanol fuelled HCCI engine for cogeneration application is very much missing in the literature. Therefore in order to meet out the simultaneous demand of power and thermal energy from a sustainable fuel in efficient and environment friendly manner, an exergy analysis of wet ethanol fuelled engine in HCCI mode for cogeneration of power and heat has been carried out in this research paper. Magnitude of exergy destruction in various components of the cogeneration cycle has been evaluated and discussed.

III. SYSTEM DESCRIPTION

A schematic diagram of the wet ethanol operated HCCI engine cogeneration system is shown in Figure 1. This schematic is adopted from Frias et al [8] and modified for cogeneration application. Ambient air enters the compressor which delivers air at high pressure and temperature followed by the regenerator, this raises the air temperature. Next liquid ethanol in water is injected into the vaporizer, where it evaporates and mixes with air. The evaporation process in the vaporizer produces a homogeneous mixture of ethanol, water vapor and air, which then enters the HCCI engine. The ethanol water air mixture inducted into the cylinder heats up as it mixes with residual gases within the cylinder. After combustion, exhaust gases enter the catalytic converter at a higher temperature and exit the converter at further higher temperature due to heat release from conversion of unburned fuel, hydrocarbon (HC) and carbon monoxide (CO) which were not reacted in the engine combustion chamber. Gases from catalytic converter at higher temperature flow into the turbine, generating power that drives the turbocharger compressor. After circulating through turbine, the exhaust gases exchange heat with the intake air in the regenerator and then leave the regenerator system at ambient pressure and higher temperature. These exhaust gases at higher temperature are assumed to be routed through the evaporator where heat transfer occurs between the exhaust stream and the organic working fluid (R113). In this study a counter flow heat exchanger (evaporator) configuration is considered to maximize heat transfer between the engine exhaust gases and the organic fluid. Thermodynamically this is preferred configuration because the temperature difference between the hot fluid and the cold fluid is minimized, thereby reducing the exergy destruction.

The heated organic vapor is then expanded in the turbine, heat is rejected to the ambient in the condenser, and the cooled working fluid is pumped with pump, back in to the evaporator. Heat of hot exhaust gas is utilized in the heat recovery steam generator to generate steam and hence to produce the process heat.

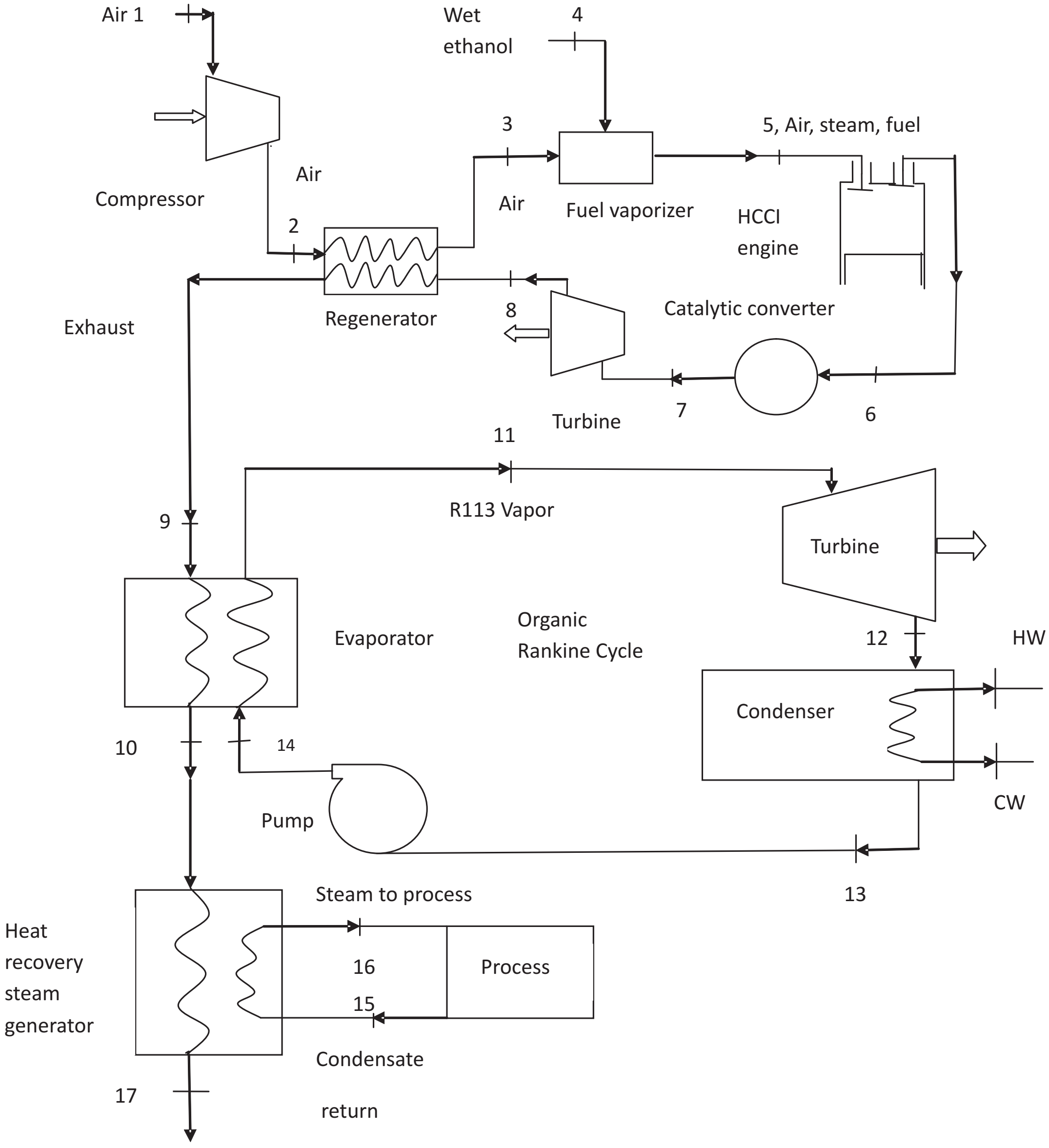

Fig. 1 The schematic diagram of wet ethanol operated HCCI engine cogeneration system with organic Rankine cycle and process steam. (Adopted from Frias et al [8] and modified for cogeneration application)

A. Exergy Destruction Model

Development of exergy destruction model shows the analyst how the performance of a system departs from the ideal limit and to what extent each component contributes to this departure, and what can be done to design better (less irreversible) systems. The general exergetic balance applied to a fixed control volume is given by Moran and Shapiro [9]

$$\sum \dot{Q}_j\left(1-\frac{T_0}{T_j}\right)-W+\sum_{in}\dot{m}_{in}\,e_{in}-\sum_{out}\dot{m}_{out}\,e_{out}-\dot{E}_D=0 \qquad [1]$$

where $\dot{Q}_j$ is the heat transfer rate to the system, W the mechanical power produced by the system, E_D the irreversibility rate or exergy destruction, and e is the flow exergy associated with the stream of matter.

$$e=\sum_i[m_i((h_i-h_0)-T_0(s_i-s_0))] \qquad [2]$$

where h_0 & s_0 represent the specific enthalpy and specific entropy at dead state respectively.

IV. RESULTS AND DISCUSSION

Cogeneration is applied to the wet ethanol operated HCCI engine system to enhance the system overall efficiency and to reduce the emissions. The exergy destruction or thermodynamic losses in each component, and the exergy efficiency of the cogeneration cycle have also been investigated under the exergy balance approach. The properties of ethanol, organic fluid (R113) and related details are taken from Heywood [10] and Perry's chemical engineers hand book [11]. Processes in the engine are typical polytropic compression and expansion and near constant volume combustion as Otto cycle [Osborne et al (2003)] [12]. Equations used for evaluating performance parameters have been referred from Trivedi et al (2010) [13] and Khaliq et al (2011) [14]. Fuel used is 35% ethanol in water mixture which improves the energy balance of ethanol production and it can efficiently run HCCI engine. [Frias *et al* (2007)] [8].

TABLE I EFFECT OF VARIATION OF AMBIENT TEMPERATURE ON EXERGY DESTRUCTION
IN DIFFERENT COMPONENTS OF THE WET ETHANOL OPERATED HCCI ENGINE COGENERATION SYSTEM FOR PR=3, HC=80% E =79%

Amb. Temp. T_0 (K)	$E_{D,}$ Turbo. comp. (kJ/kg)	$E_{D,}$ Regenator (kJ/kg)	$E_{D,}$ Fuel Vap. (kJ/kg)	$E_{D,}$ HCCI Engine (kJ/kg)	$E_{D,Cat.}$ Conv. (kJ/kg)	$E_{D,}$ Turbo Turbine (kJ/kg)	$E_{D, ORC}$ HRSG (kJ/kg)	$E_{D, ORC}$ Turbine (kJ/kg)	$E_{D,}$ Condenser (kJ/kg)	$E_{D, ORC}$ Pump (kJ/kg)	$E_{D,}$ Cogen. HRSG (kJ/kg)	$E_{D,}$ Exergy lost to Env. (kJ/kg)
290	23.540	75.732	67.018	2815.001	126.849	19.719	20.122	3.422	15.130	0.421	17.408	30.788
295	24.022	74.037	66.006	2816.315	127.341	19.984	21.739	3.747	14.189	0.461	17.708	28.858
300	24.509	72.409	65.003	2817.591	127.673	20.242	23.460	4.088	12.886	0.503	18.008	27.028
305	25.003	70.528	64.029	2818.818	127.796	20.490	25.425	4.472	11.517	0.551	18.308	25.298
310	25.503	68.957	62.984	2820.056	128.041	20.743	27.328	4.836	9.491	0.596	18.609	23.666

TABLE II EFFECT OF VARIATION OF TURBOCHARGER PRESSURE RATIO ON EXERGY DESTRUCTION IN DIFFERENT
COMPONENTS OF THE WET ETHANOL OPERATED HCCI ENGINE COGENERATION SYSTEM FOR T0=300 K, HC=80%, E =79%

Pr. Ratio Pr	$E_{D,}$ Turbo. comp. (kJ/kg)	$E_{D,}$ Regenator (kJ/kg)	$E_{D,}$ Fuel Vap. (kJ/kg)	$E_{D,}$ HCCI Engine (kJ/kg)	$E_{D,Cat.}$ Conv. (kJ/kg)	$E_{D,}$ Turbo Turbine (kJ/kg)	$E_{D, ORC}$ HRSG (kJ/kg)	$E_{D, ORC}$ Turbine (kJ/kg)	$E_{D,}$ Condenser (kJ/kg)	$E_{D, ORC}$ Pump (kJ/kg)	$E_{D,}$ Cogen. HRSG (kJ/kg)	$E_{D,}$ Exergy lost to Env. (kJ/kg)
2.50	20.235	89.504	76.701	2814.00	128.144	14.652	22.663	3.926	12.373	0.483	18.008	27.028
2.75	22.454	80.246	70.546	2815.884	127.805	17.526	23.038	4.002	12.615	0.493	18.008	27.028
3.00	24.509	72.409	65.003	2817.591	127.673	20.242	23.460	4.088	12.886	0.503	18.008	27.028
3.25	26.428	65.580	60.095	2819.070	127.273	22.797	24.088	4.215	13.285	0.519	18.008	27.028
3.50	28.230	59.105	55.595	2820.433	127.026	25.229	24.932	4.383	13.816	0.540	18.008	27.028

Table I & II reveals the exergy destruction in each component of wet ethanol operated HCCI engine cogeneration system. This exergy study shows that the maximum exergy is destroyed in the HCCI engine which is 2817.591kJ/kg at mean operating conditions. Exergy destruction in Heat transfer processes e.g. regenerator and fuel vaporizer accounts for about 72.409kJ/kg and 65.003kJ/kg respectively at mean conditions. The exergy destruction in catalytic converter is 127.673kJ/kg. The exergy destruction in HCCI engine and catalytic converter is high because the effect of chemical exergy in these components predominates over the effect of physical exergy. Exergy destruction in ORC evaporator, ORC turbine, ORC condenser, pump and cogeneration heat recovery steam generator (HRSG) is very less compared to main HCCI engine components. It indicates that the exergy analysis is providing ranking among the components of the system. The component with higher exergy destruction is very much responsible to deteriorate the performance of the system as compared to the components with lower exergy destruction. It further indicates that which component needs to be repaired or serviced first for maintenance purpose.

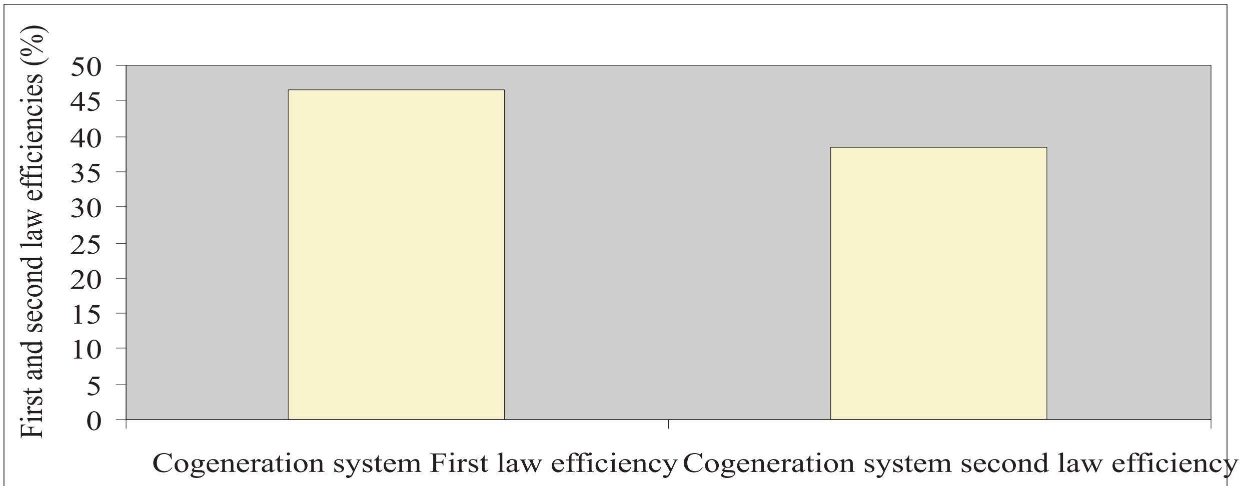

Figure 2. First and second law efficiency of wet ethanol based HCCI engine cogeneration system at mean operating conditions

Figure 2 clearly indicates that cogeneration system has a good thermal performance with first and second law efficiencies of 46.47% and 38.5% respectively for the mean operating conditions of T_0=300K, Pr=3, η_C=80%. Thus the recovery of waste heat is considerably increasing the system efficiency. That is why various engineering applications throughout the world are considering cogeneration system for improving efficiency.

V. CONCLUSION

In this article, the thermodynamic analysis of the wet ethanol operated HCCI engine cogeneration system is performed. The exergy analysis is aimed to evaluate the exergy destruction in each component as well as the exergetic efficiencies. The fuel used is 35% ethanol in water mixture and this blend is directly formed in the process of ethanol production from biomass. This study further explores the use of wet ethanol as a fuel for HCCI engines while using exhaust heat recovery to provide the high input energy required for igniting wet ethanol. The heat exchanger (regenerator) was used to preheat the intake air allowing HCCI combustion without electrical air heating. The thermal efficiency of the overall plant is found to be 46.47% and the exergetic efficiency is 38.5%. The results of this study show that HCCI engines can use ethanol fuels with 35% ethanol in water mixture while maintaining favorable operating conditions. This can remove the need for the most energy-intensive portion of the water removal processes i.e. distillation and dehydration of wet ethanol during ethanol production.

The main conclusions from the current study can be summarized as follows:

1. HCCI combustion process is highly different from combustion process of SI and CI engines as it lacks flame propagation therefore it has superior potential for

achieving high thermal efficiency compared to SI or CI engine. It is concluded that the cogeneration cycle has a good thermal performance with first and second law efficiencies of 46.47% and 38.5% respectively for the mean operating conditions of T_0=300K, Pr=3, η_C=80%.

2. Maximum exergy was destroyed in the HCCI engine which is 2817.59kJ/kg at mean operating conditions. Exergy destruction in Heat transfer processes e.g. regenerator and fuel vaporizer accounts for about 72.409kJ/kg and 65.003kJ/kg respectively at mean conditions. The exergy destruction in catalytic converter is 127.673kJ/kg.
3. The exergy destruction in HCCI engine and catalytic converter is high because the effect of chemical exergy in these components predominates over the effect of physical exergy.
4. Exergy destruction in ORC evaporator, ORC turbine, ORC condenser, pump and cogeneration heat recovery steam generator (HRSG) is very less compared to main HCCI engine components.
5. It indicates that the exergy analysis is providing ranking among the components of the system. The component with higher exergy destruction is very much responsible to deteriorate the performance of the system as compared to the components with lower exergy destruction. It further indicates that which component needs to be repaired or serviced first.

Heat recovery from automotive engines has been predominantly for turbo-charging or for cabin heating. Studies relative to application of the recovered heat to run organic Rankine cycle (ORC) is scarce. In this paper an ORC is attached with hot exhaust gases of HCCI engine. Mathematical model results suggest that the concept is thermodynamically feasible and could significantly enhance system performance of the engine. It will largely benefit considering the cost advantage particularly fuel cost in long run and emission control. This would definitely provide a right platform for rapid and qualitative development of internal combustion engines and will bring economic development.

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