ENERGY RECOVERY FROM DIESEL ENGINE EXHAUST GASES FOR PERFORMANCE ENHANCEMENT AND AIR CONDITIONING

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ABSTRACT. *The utilisation of exhaust waste heat is now well known and the forms the basis of many combined cooling and power installations. The exhaust gases from such installations represent a significant amount of thermal energy that traditionally has been used for combined heat and power applications. This paper explores the theoretical performance of four different configurations of a turbocharger Diesel engine and absorption refrigeration unit combination when operating in a high ambient day temperature of 35°C. The simulation is performed using "SPICE", a well known programme commonly used for engine performance predictions. The paper examines the interfacing of the turbocharged Diesel engine with an absorption refrigeration unit and estimates the performance enhancement. The influence of the cycle configuration and performance parameters on the performance of the engine operating as a power supply with an auxiliary air conditioning plant is examined. It is demonstrated that a pre and inter cooled turbocharger engine configuration cycle offers considerable benefits in terms of SFC, efficiency and output for the Diesel cycle performance.*

KEYWORDS: Diesel engine, combined cooling and power, absorption refrigeration, SPICE

1-INTRODUCTION

Research in thermodynamic power cycles over the past two decades has shown improvements in thermal power plant efficiencies. Many combined cycles have been suggested as alternative to the conventional power cycles for improving the overall energy conversion efficiency. These systems that produced space heating have the additional advantage that the heating and electrical loads do not occur simultaneously. Electricity is produced during the summer when the demand for electricity to power air-conditioning systems is high. Comfort heat is produced during the winter when the need is the greatest. CHP systems then have a high utilisation when compared to pure cooling or pure electrical systems, which are only partially, used in certain seasons of the year.

Combined heat and power production has economical as well as environmental advantages, as the utilisation of the energy can be more than doubled compared to power production alone, [1]. Energy recovery from various waste heat sources such as Diesel engines exhaust and cooling energies has become a world-wide interest since the energy crises, [2]. In applications where it is advantageous to use a Diesel engine as a prime mover it is generally necessary on the grounds of economy to recover a large proportion of the waste heat generated, rather than reject it to the atmosphere.

Generally, the utilisation of waste heat technologies is basically known for many engineering applications. The absorption chilling cycle is one that operates on several heat sources and is thus ideal for heat recovery applications and is not only increased its efficiency but its ability to recover exhaust heat directly with the aid of a waste steam boiler [3]. The feasibility of vehicle air conditioning by exhaust gas operated open cycle absorption cooling system at full load has been studied and it has been shown that the cooling potential in the exhaust gas is much greater than the required for cooling of the vehicles interior space [4]. It was demonstrated that an open-cycle absorption-cooling unit can be integrated with the engine and the operating cost was almost negligible. The feasibility of an exhaust gas actuated closed cycle absorption refrigeration system for a low temperature application by using the ammonia-water combination have been demonstrated and it can be concluded that for low temperature application, the system can be suitably installed and successfully operated [5].

In recent years, there has been increased interest in integrating systems for combined heat and power, [6], otherwise known as cogeneration, which may be defined as a thermal system that produces electrical and heat energy simultaneously from a single source of fuel, [7]. The idea to be investigated here is based essentially on the fact that, the exhaust gases from Diesel engines represent an appreciable energy loss to the environment. Therefore, it is possible that some of this waste energy could be used for charge air cooling as well as improving the thermal efficiency of the Diesel engine.

Combined cooling and power (CCP), which is defined as a thermal system that produces external work and heat based cooling effect simultaneously from a single source of fuel. It is an application of waste heat energy recovery that utilizes hot waste gases to improve plant efficiency and power output, usually without increasing

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fuel consumption or exhaust emissions. Recent technological advances have made CCP systems more efficient and less expensive.

This paper explores the theoretical performance of four different configurations of a turbocharged Diesel engine and absorption refrigeration unit combination when operating in a high ambient day temperature of 35-40 °C. The results were compared and the most suitable configuration cycle was chosen. Consideration has been given to the coefficient of performance of the unit and the heat exchangers efficiency, the exhaust temperature, mass flow, the amount of cooling capacity available in the exhaust gases, and the cooling capacity of the absorption unit for the different configuration studied.

2-SYSTEM DESCRIPTION

The Caterpillar Diesel engine used in this work comprises four major components, namely, a compressor, an inter-cooler, a Diesel unit, and a turbine. A decrease in the intake temperature decreases the mass flow through the compressor. In addition, the pressure ratio is decreased, and, as a result, less energy can be added by combustion to this less dense charge to produce a given turbine inlet temperature. Therefore, to overcome the above, a pre-cooler is introduced to the system when the ambient temperature is 35°C or above.

A schematic view of the Diesel-Absorption system is shown in Figs (1), (2), (3), and (4). The engine is provided with chilled water from the absorption unit in the configurations shown. The configurations examined were:

1-Pre-inetr cooler engine, Fig (1)

2-Inter cooled combination engine, Fig (2),

3-A pre cooled engine and, Fig (3).

4-Non-cooled engine, Fig (4),

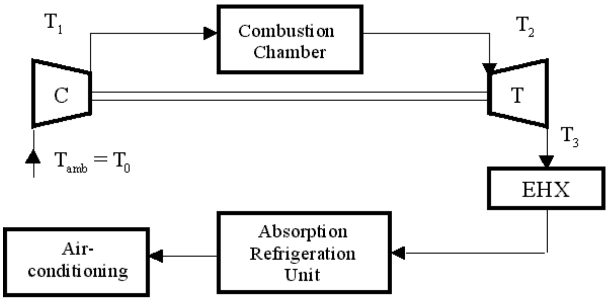

Figure 1. Schematic diagram of combined non-cooled with absorption refrigeration Unit

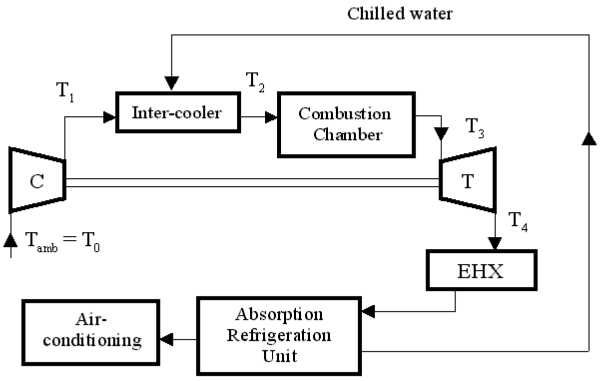

Figure 2. Schematic diagram of combined inter cooled with absorption refrigeration Unit

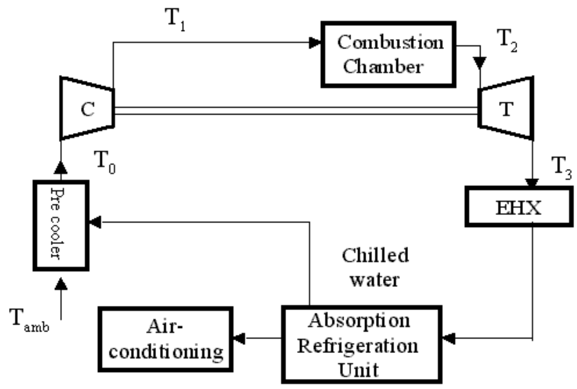

Figure 3. Schematic diagram of combined pre cooled turbocharged with absorption refrigeration unit

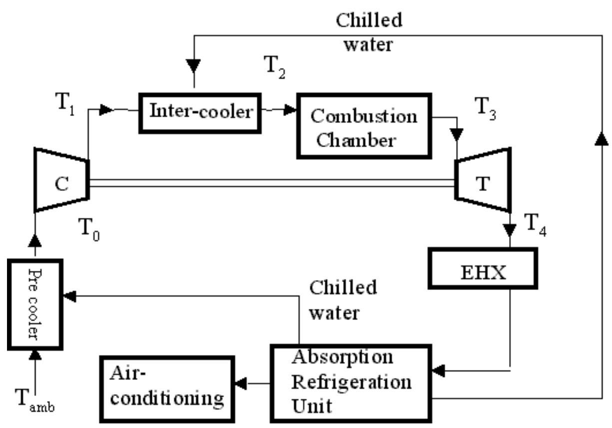

Figure 4. Schematic diagram of turbocharged with pre and inter cooling Diesel engine cycle

The thermal energy in the exhaust gases was transferred through a heat exchanger to the water circulated via the evaporator of the absorption unit. The charge air temperature at exit of both the inter cooler and pre cooler was 10 °C being cooled using chilled water that was circulated in the absorption unit. The system simulation procedure consisted of interfacing the SPICE program, [7] with the appropriate charge air pre cooler, exhaust gas heat exchanger and coolant loop, absorption unit and chilled water-cooling circuit. An option within the SPICE programme allowed an inter cooler to be included in the engine simulation. A schematic diagram of the computational model is shown in Fig. (5). It can be seen that the SPICE forms the major component of the computational model and it is connected to subroutines that determine the performance of the absorption unit and the additional heat exchangers not included in SPICE. SPICE uses an iterative technique to determine the operating point of the Diesel engine from a set of input file data. The presence of the pre-cooler changes the inlet conditions of the turbocharger compressor and exhaust gas heat exchangers effect the turbine pressure ratio and hence the matching point of the compressor and turbine. It is necessary to introduce a second iterative loop outside the SPICE programme that defines the operating conditions of the heat exchangers and absorption unit and recreates the SPICE data input file for a subsequent execution of SPICE.

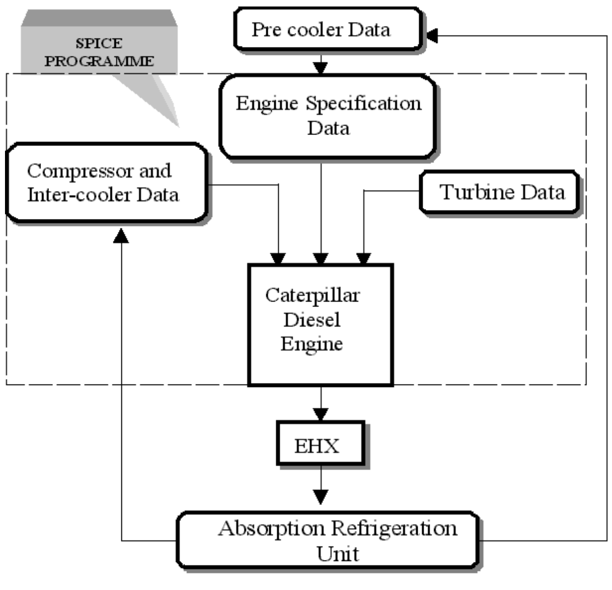

Figure 5. Inter-facing the SPICE programme with the thermodynamic cycle

3-THERMAL ANALYSIS

The purpose of the thermal analysis is to analyse the energy flow in the combined cycle to determine from the Diesel engine simulation the energy available in the exhaust gases for driving the absorption cycle, the cooling capacity overall from the exhaust gases. The Diesel cycle simulation provides an analysis for different configuration of Diesel engine i.e., non cooled, pre cooler, inter cooler, pre-inter cooler, thus the result from this part of the simulation are used as an input to the absorption cycle. It is thus possible to determine the configuration of the combined cycle that would be most appropriate for a particular combination of cooling requirement and shaft work.

To determine the performance of the waste heat powered refrigeration system, the mass flow rate and the exhaust temperature of the engine must be known. The exhaust temperature of the engine at different ambient temperature is calculated using the procedures described in the previous chapter. The following section gives details of the analysis perform to assess the performed of the combined cycle:

3.1 Cooling Capacity Available in the Exhaust Gases:

It is important to first estimate the maximum cooling capacity available in the exhaust gases. For a given speed, computer program calculates the exhaust mass flow and temperature. The basic equation to calculate the available chilled water from the hot gas stream is calculated by, [9]:

$$Q_{ex} = \dot{m} \times c_p \times \left(T_{out,ex} - T_{in,ex}\right) \times 0.97 \qquad (1)$$

Where,

$\dot{m}$ is the mass flow rate kg/sec.

c_p is the average specific heat.

$T_{in.ex}$ is the inlet gas temperature to the heat exchanger.

$T_{out,ex}$ is the outlet gas temperature from the heat exchanger.

0.97 is the transmission losses (duct work).

3.2 Cooling Capacity for Charge Air Cooling:

The amount of cooling capacity required for charge air cooling (pre and/or inter cooler) is very much dependent on the temperature reduction of the charge air due to cooling process and the effectiveness of the heat exchanger incorporated in the system. Therefore the energy transfer from the charge air is:

$$Q_{i/p} = m_c \times c_p \left(T_o - T_i\right) \qquad (2)$$

3.3 Cooling Capacity of Absorption Unit:

Applying the above formulae for calculating the cooling capacity available in the exhaust gases for different cycle configurations. Tables 3.8 to 3.12 shows the cooling capacity for the foregoing cycles. It can be seen that, there is a sufficient amount of energy in the exhaust gas for the cooling purposes. This energy can be introduced to an absorption unit and by considering the efficiency of heat exchangers and the coefficient performance of the absorption refrigeration machine, the amount of cooling capacity available in the exhaust gases can be used for charge air (pre and inter cooler) or air conditioning or both.

When the waste heat is to be converted and used to produce chilled water, the amount of energy in the form of heat delivered to the absorption unit is:

$$Q_{in} = \eta_{HE} \times Q_{ex} \quad (3)$$

The cooling capacity available from the absorption unit is:

$$Q_{cool} = COP \times Q_{in} \quad (4)$$

Where,

Q_{cool} is the cooling produced, kW

COP is the performance of coefficient of the absorption unit.

3.4 Cooling Capacity for air-conditioning:

The surplus cooling capacity produced by the absorption unit that is not used in the charge cooling will be available for environmental air conditioning. The cycles examined in this section are as follows:

Non-cooled engine;

For non-cooled turbocharger Diesel engine, the amount of cooling capacity for air conditioning is equal to the amount of cooling capacity available from the combined cycle. Therefore;

$$Q_{air\text{-}cond} = Q_{cool} \quad (5)$$

Inter-cooled engine;

For turbocharger engine with inter cooling, the amount of cooling capacity for air conditioning is equal to the difference between the amount of cooling capacity available from the combined cycle, and the amount of cooling is used for inter cooling. Cooling capacity for inter cooler is depend on the temperature difference and the mass flow rate:

$$Q_{air\text{-}cond} = Q_{cool} - Q_{inter\ cooler} \quad (6)$$

Pre-cooled engine;

For turbocharger engine with pre-cooling, the amount of cooling capacity for air conditioning is equal to the difference between the amount of cooling capacity available from the combined cycle, and the amount of cooling is used for pre cooling;

$$Q_{air\text{-}cond} = Q_{cool} - Q_{pre\ cooler} \quad (7)$$

Pre-Inter cooled engine;

For turbocharger engine with pre and inter cooling, the amount of cooling capacity for air conditioning is equal to the difference between the amount of cooling capacity available from the combined cycle, and the amount of cooling is used for pre and inter cooling. The amount of cooling capacity required for pre and inter cooling is directly related to temperature of the charge air due to the cooling process and the efficiency of the heat exchangers that have been used:

$$Q_{air\text{-}cond} = Q_{cool} - Q_{pre\ cooler} - Q_{inter\ cooler} \quad (8)$$

Since there are two usable energy outputs from a CCP system, defining overall system efficiency is more complex than with simple systems. The system can be viewed as two subsystems, the power system, which is an engine and the heat recovery system, which is an absorption refrigeration cycle. The efficiency of the overall system results from an interaction between the individual efficiencies of the cooling and power systems.
The overall efficiency of the cycle is defined as the cooling capacity of the absorption cycle (kW) divided by the energy input to the engine from the fuel plus the thermal efficiency of the engine:

$$\eta_{overall} = \frac{Q_{ab}}{Q_{in}} + \eta_{th} \quad (9)$$

where:

Q_{ab} is the cooling capacity of the absorption cycle

η_{th} is the thermal efficiency of the engine.

Q_{in} is the energy input to the cycle

4-DISCUSSION AND RESULTS

Heat for absorption cooling is recovered from a Diesel engine and used in process cooling or to reduce the temperature of the ambient in order to increase the efficiency of the engine. Cooling of the inlet air of a Diesel engine in high ambient operation makes the air more dense, giving the machine a higher mass flow. This results in an increase in the engine output and its efficiency. The SPICE programme is used on four different configuration cycles. The influences of cycle configurations on the engine performance are clearly noticed; it was showed that decreasing the inlet temperature entering to the system would increase the mass flow.

The results of the cycle simulation are shown in Tables (1) and (2). Table (1) relates to the output from the SPICE programme and the operational parameters of the absorption unit are shown in Table (2). The performance of the Diesel engine as predicted by the simulation is broadly as expected. The air consumption increases with charge air cooling as does the power and efficiency. The exhaust gas temperature and BSFC both decreases with increased charge air-cooling. The results relating to the absorption unit are more interesting. If the need for air conditioning is greater than that for shaft power then a minimum of charge air-cooling is required consistent with maintaining the thermal loading of the engine within accepted bounds. The high exhaust temperatures resulting from the high charge inlet temperatures of the cycles with no or a small amount of charge air cooling produces a high cooling capacity in the absorption unit that off sets to some extent the lower brake thermal efficiency of the Diesel engine. An inherent disadvantage of a single effect absorption cycle, however, is its low coefficient of performance. This will effect the capacity of the absorption unit. As the charge air-cooling is increased, the Diesel cycle efficiency increases at the expense of lowering the exhaust temperature at inlet to the absorption unit. This reduces the cooling capacity available at the exhaust heat exchanger. Furthermore, it reduces the capacity of the absorption unit, which can result in the overall efficiency of the combined cycle as shown in Table (2) being reduced.

5-CONCLUSION

With the aim of reducing energy consumption a combined cooling and power system was the main idea of this paper. It will not only produce power but also provide a certain amount of cooling. An absorption refrigeration unit interfaced with a Caterpillar Diesel engine has been used for cooling the charge air prior to ingestion to the engine cylinder or for other cooling purposes such as air conditioning and it was demonstrated that a Diesel-absorption unit combination is a practical possibility.
The investigation is conducted with regard to its feasibility to enhance the efficiency and capacity for cooling applications. Operating parameters and the heat duties are also studied. The study of these results shows that it is quit obvious that much has been achieved in the combined cycles. It has been shown that a Diesel-absorption combined cycle with pre-inter cooling will have a higher power output and a thermal efficiency than the other configurations. On the other hand the overall efficiency of a pre-inter cooled cycle is lower than that of the inter cooler. Clearly there is a requirement for further analysis considering other aspects such as economic analysis that have not been considered in this paper.

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NOTATION

c_p	Specific heat at constant pressure
C	Compressor
CCP	Combined cooling and power
CHP	Combined heat and power
COP	Coefficient of performance
SFC	Specific fuel consumption
SPICE	Simulation Programme for Internal Combustion Engines
EHX	Exhaust heat exchanger
HE	Heat exchanger
m	Mass flow rate[kg/s]
Q	Heat quantity [kW]
T	Turbine, Temperature [K]
η_{HE}	Heat exchanger effectiveness

Subscripts

1-5	Stations in absorption-Diesel cycle
amb	Ambient
ex	Exhaust
in	Inlet
out	Outlet

Table (1) Performance of the different configurations at an ambient temperature 35^{o}C.

Engine configuration	No charge air cooling	With pre cooler only	With inter cooler	With pre and inter cooler
Engine speed [RPM]	2000	2000	2000	2000
Inlet manifold temp. [K]	434	414	334	329
Power [kW]	154.8	159.6	165	167.4
Exhaust temp. [K]	1000	951	890	860
BSFC [gm/kW hr]	211.4	207.4	200.7	198.2
Air entering system [kg/s]	0.09135	0.09607	0.09834	0.1023
Air leaving system[kg/s]	0.0958	0.101	0.103	0.107
Brake thermal efficiency [%]	38.51	39.25	40.56	41.0
Energy to exhaust [%]	38.35	38.48	36.49	34.05
Energy to coolant [%]	18.15	17.37	14.96	14.71

Table (2) Performance of the combined cycle

Engine configuration	No charge air cooling	With pre cooler only	With inter cooler	With pre and inter cooler
Engine speed [RPM]	2000	2000	2000	2000
Thermal power in exhaust gases [kW]	52.97	50.94	46.15	44.93
Cooling capacity of absorption unit [kW]	35.49	34.1307	30.9	30.102
Cooling capacity of charge air cooling [kW]	0.0	0.97	3.56	4.157
Cooling capacity of air conditioning [kW]	35.49	33.16	27.34	25.95
Overall cycle efficiency [%]	58.21	58.33	60.61	57.81