Design and Optimization of Internal Combustion Engine Based Co-Generation System Using Integrated Thermal Management Controller

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Abstract - *Waste heat recovery systems are gaining prominence day to day due to increased plant efficiencies with lesser heat losses resulting in gain in economy irrespective of the fuel used. Application of cogeneration to internal combustion engines results in higher fuel economies. In this work, attempts are made to recover the waste heat by preheating the air with the help of integrated thermal management controller and increasing the cooling water temperature at outlet. A heat pipe with Water/R22 as working fluid is used to transfer the waste heat for the preheating of air supplied to the engine. This design is optimized using genetic algorithm. It has been observed that the thermal efficiency is increased with a slight reduction in fuel consumption. In addition, the experimental results obtained are in well agreement with those obtained by optimization.*

Keywords*:* *Cogeneration, ICEngine, Heat pipe, efficiency*

I. INTRODUCTION

To improve the thermal efficiency of heat engines, the waste heat available in the exhaust gases is to be recovered. This in turn reduces the greenhouse gas emissions. Lot of research work has been carried out on waste heat recovery systems. Ioan Saucius et. al. [1] introduced the concept of variable conductance heat pipe (VCHP) for controlling the temperature of solar collectors. Performance of VCHP is analyzed experimentally by considering the working fluid as water with air as non-condensing gas. Huangfu et. al. [2] studied the characteristics of I C Engine based cogeneration system with heat recovery from engine cooling water and exhaust gases. Khan et. al [4] presented the analysis of cogeneration of double-effect absorption chiller with and without thermal energy storage applied to an institutional building. Hycienth I. Onovwiona et. al [5] proposed a mathematical model to assess the design and techno-economic aspects of I.C engines based cogeneration system. The parametric model provides useful information about the cogeneration system performance in response to a building's electrical and thermal demands. R. Yoshi et. al [6] proposed a new HVAC system for condominiums that make use of solar heat and outdoor cool air and found that the proposed system has high performance for both energy saving and thermal comfort. Farahat et. at [9] performed exergy optimization of flat plate solar collectors by considering the absorber plate area, dimensions of solar collector, pipes' diameter, mass flow rate, fluid inlet, outlet temperature, the overall loss coefficient, etc. as variables. Mehdi Aliehyaei et al. [11] reported the exergy, economy, and environmental analysis of simple and combined heat and power internal combustion engines. It has been observed that entropy generation in the combined heat and power mode is 30% lower than that in the simple internal combustion engine.

This work aims to study the performance of the variable conductance heat pipe such that the heat pipe absorbs maximum amount of heat from the exhaust gases. The performance of the heat pipe which is integrated with the internal combustion engine and its effect on the temperature control in varying working conditions are studied. The optimum values of different controllable parameters are obtained in order to achieve maximum thermal efficiency.
by carrying out rigorous experiments using MATLAB.

II. EXPERIMENTAL SETUP

i. Design of VCHP

The design of the integrated thermal management controller (ITMC) experiment prototype is based on flat-front model, which assume a sharp vapor/non-condensable gas interface.

The assumptions of the model are as follows:

1. The ITMC is in steady operating conditions.
2. The non-condensable gas remains stationary, does not mix with the working medium, does not re-circulation and has the same temperature as ambient.
3. Heat loss from the outer wall of ITMC is negligible.
4. Both the vapor and the non-condensable gas follow the ideal gas law.
5. The effect of buoyancy force on the gas motion is neglected.

ii. For Evaporator section:

Volume = 10^{-3} m^3
Mass of water circulated = 1 kg
Density of water = 1000 kg/m^3
Radius of the chamber = 3.75 cm
Length of the chamber = 30 cm

iii. For condenser section:

Assuming volume of condenser twice the volume of evaporator i.e. Vc= 2Ve

For Gas Reservoir

Radius of reservoir = 10 cm,
Length of the reservoir = 15.3 cm

iv. Selection of working fluid:

Good working fluid requires big value of λMv/R at the vapor temperature and small value of Pv0/Pv at cooling water temperature, where - λ is the latent heat of vaporization and Mv is the molecular weight of vapor. In this work, water is chosen as the working fluid.

v. Evacuation and charging of VCHP

For the working of the variable conductance heat pipe, it is to be charged with a working fluid (water) and non-condensable gas (R22). The heat pipe is to be filled with 1.3lit. of water and 13.84gm. of R22.
The following set up is designed and fabricated in order to charge the heat pipe.

- Complete evacuation of the heat pipe through the vacuum pump.
- Filling the heat pipe with 1.3lit. of water.
- Charging the heat pipe with 13.84gm. of R22.

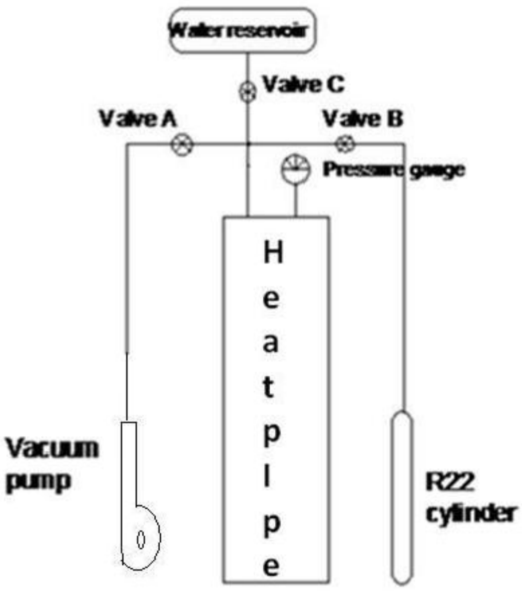

Fig. 1 Charging circuit for VCHP

Construction:

The heat pipe is integrated with 5HP Canon engine. The VCHP is wickless vertical cylindrical heat pipe. The working fluid selected is water and the non-condensable gas used is R-22. The heat source used is exhaust gases from the engine and heat rejection from the heat pipe is effected by circulating engine cooling water and air. The evaporator section is connected to the exhaust manifold of the engine. Provision is also made for the exhaust gas to bypass to the
atmosphere in the event of excess pressure building up in the heat pipe header section.
The condenser section is connected to the inlet manifold of the engine through a flexible tube of diameter 18.75mm through which water is flowing and 6mm dia. tube through which air is flowing. The flow diagram is as shown in the fig 2.

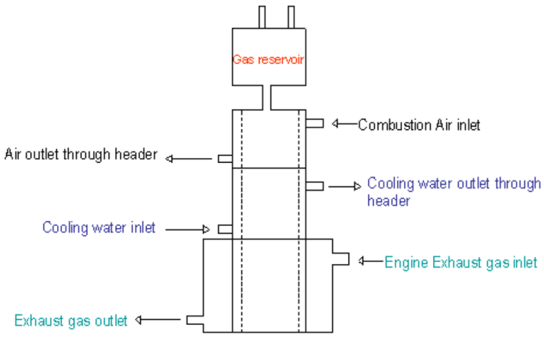

Fig. 2. Experimental Setup

III. EXPERIMENTAL PROCEDURE

Experimental procedure includes calculations of the effectiveness of the heat pipe and the brake thermal efficiency of the engine. The heat input to the evaporator of VCHP is coming from the exhaust gases of the IC engine. The working fluid (water) evaporates by taking latent heat from the exhaust gases. This vapor travels to the condenser section because of the pressure difference and gets condensed in the condenser by rejecting heat to the heat sink.
At the condenser, engine cooling water and combustion air are circulated. Heat that is rejected from water vapor will be taken by air and cooling water.

Two experiments are conducted:

- ☐ Firstly, to find out the effect of pre-heating the inlet air and regulating the cooling water temperature on the engine performance.
- ☐ Secondly, to determine the effectiveness of the heat pipe in transferring heat from one region to another region.

III. OPTIMIZATION

By using experiment values of parameters like mass flow rate of air, exhaust gas and water, and temperatures of air, exhaust gas and water. Genetic algorithm is used to write the program for optimization.
Two objective functions are defined in this work,
(i) To maximize the thermal efficiency of the engine
Maximize $\eta_{bth} = f\,(F.C, m_a, m_{ex}, m_w, T_{exi}, T_{wi}, T_{wo}, T_{ai})$
(ii) To maximize the effectiveness of heat pipe
Maximize $\epsilon = f\,(Texi, Texo, Two, Tao, mex, ma, mw,)$

IV. RESULTS AND DISCUSSION:

Engine is made to operate at different loads 0.63 kW, 3.09 kW, 4.92 kW and varying mass flow rates of cooling water.

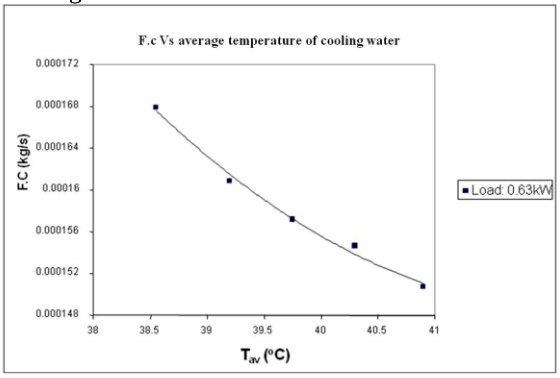

Fig. 3 Fuel consumption Vs Average temperature of cooling water at 0.63 kW

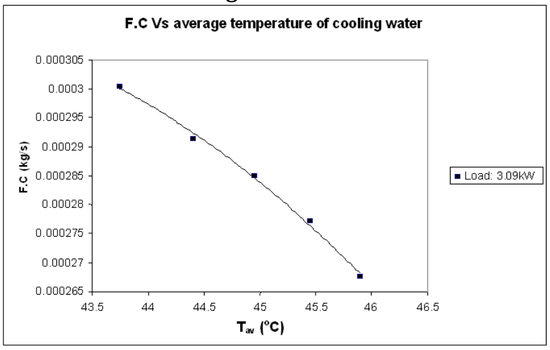

Fig. 4 Fuel consumption Vs Average temperature of cooling water at 3.09 kW

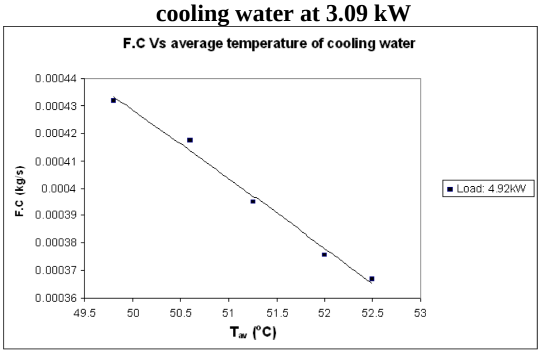

Fig. 5 Fuel consumption Vs Average temperature of cooling water at 4.92 kW

Figures 3, 4 and 5 represents the variation of fuel consumption for different loads operated with different cooling water temperatures. It has been observed that there is a slight reduction in the fuel consumption with the increase in average temperature. As the average temperature of cooling water increases, the temperature difference between cooling water and engine decreases. So the heat losses from the engine decreases. It decreases the heat to be supplied to the engine from the fuel. So fuel consumption is decreased.

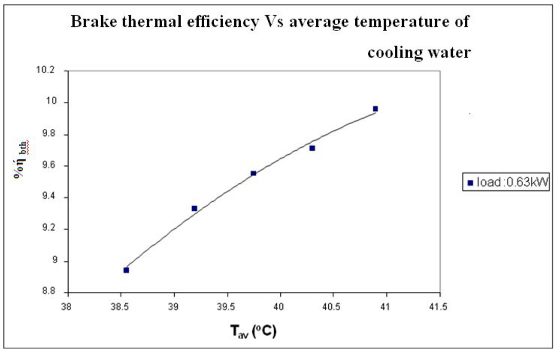

Fig. 6 Brake thermal efficiency Vs Average temperature of cooling water at 0.63 kW

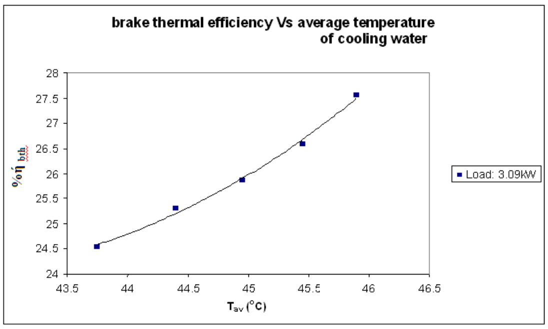

Fig. 7 Brake thermal efficiency Vs Average temperature of cooling water at 3.09 kW

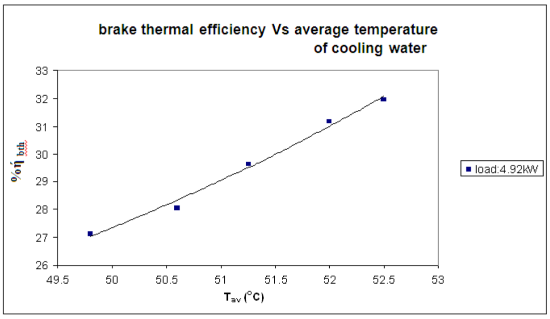

Fig. 8 Brake thermal efficiency vs Average temperature of cooling water at 4.92 kW

Figures 6, 7, and 8 shows the variation of brake thermal efficiency with average temperature of cooling water at various loads. As the average temperature of cooling water increases the loss of heat from the engine decreases which leads to increases of brake thermal efficiency. As the test is performed at constant load, the brake thermal efficiency increases due to reduction of fuel consumption.

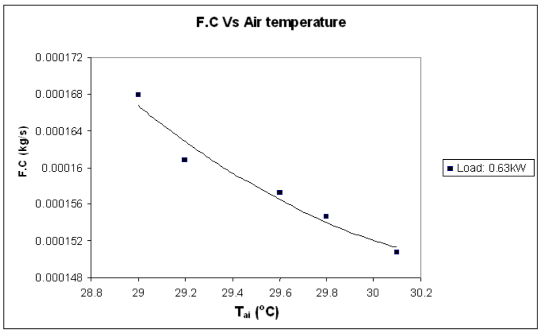

Fig. 9 Fuel consumption Vs Air temperature at 0.63 kW

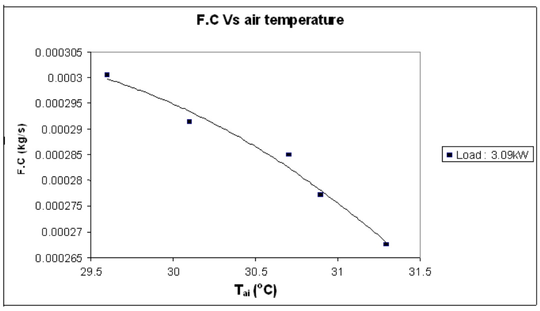

Fig. 10 Fuel consumption Vs Air temperature at 3.09 kW

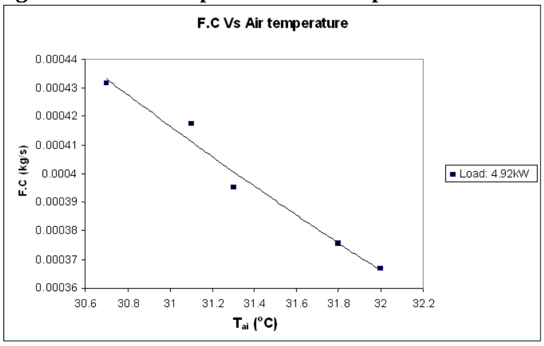

Fig. 11 Fuel consumption vs Air temperature at 4.92 kW

Figures 9, 10, and 11 shows the variation of brake thermal efficiency with average temperature of cooling water at various loads. As the air temperature increases, the amount of work required to raise the combustion temperature decrease, in addition, complete combustion of the fuel also is taking place. So the required power output can be obtained with less quantity of the fuel and hence fuel consumption decreases.

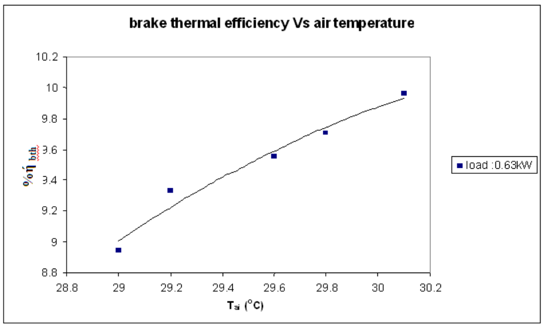

Fig. 12 Brake thermal efficiency vs Air temperature at 0.63 kW

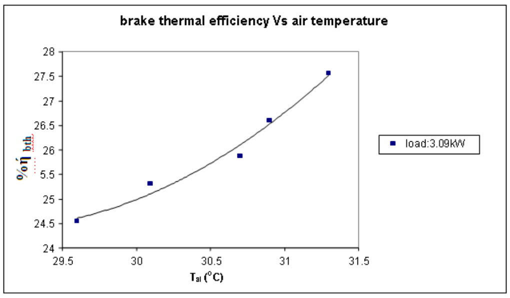

Fig. 13 Brake thermal efficiency Vs Air temperature at 3.09 kW

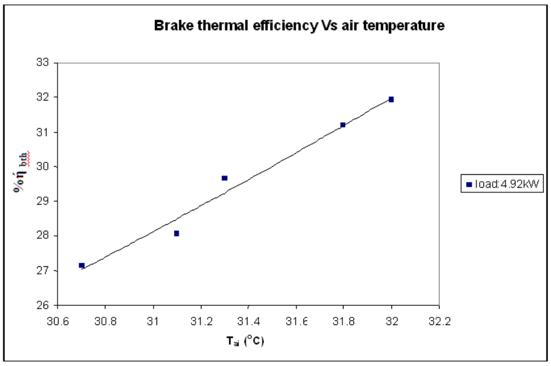

Fig. 14 Brake thermal efficiency Vs Air temperature at 4.92 kW

Figures 12, 13, and 14 shows the variation of brake thermal efficiency with air inlet temperature of engine at different loads. As the air temperature increases effective combustion occurring, so the fuel consumption decreases. As the fuel consumption decreases, the brake thermal efficiency increases since the test is performed at constant load.

Comparison of experimental results with Optimized values

The following table 1 shows the comparison of optimized values of various engine parameters with experimental values. It has been observed that the values are in good agreement with each other.

Table 1. Comparison of Optimized and Experimental Values

Parameters	Experiment values	Optimized values
Brake power (kW)	4.93	4.92
Fuel consumption (kg/s)	$3.6021*10^{-04}$	$3.6712*10^{-04}$
Mass flow rate of air (kg/s)	0.0120	0.01196
Mass flow rate of exhaust (kg/s)	0.0124	0.01233
Mass flow rate of water (kg/s)	0.0268	0.020868
Temperature of exhaust gas (°C)	387.0297	373.52
Temperature of cooling water inlet (°C)	37.4646	37.4
Temperature of cooling water outlet (°C)	66.8020	66.6
Temperature of air inlet (°C)	32.0966	32.2

V. CONCLUSION

A prototype of integrated thermal management controller is fabricated and the design is optimized. Through analysis of experimental data, the following conclusions can be drawn:

1. The brake thermal efficiency is sensitive to the cooling water temperature. Therefore it is important to control the cooling water temperature.

2. The following factors can make the rise of cooling water temperature
   a. The increasing of heating power.
   b. The decrease of cooling water flow rate.
3. At maximum load condition, the cooling water average temperature is increased from 49^0C to 53^0C and Thermal Efficiency increases from 27% to 32%.
4. As the air temperature increases mildly combustion occurs effectively and the fuel consumption decreases and small increment is found in Thermal efficiency.
5. The experimental values are well matching with optimized values obtained from algorithm.

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