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Exhaust Heat Co-Generation System Using Phase Change Cooling for Heavy Duty Vehicle

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ABSTRACT

A waste heat recovery system composed of a two phase cooling system, an exhaust heat exchanger, and mini-turbine (expander) has been proposed by Henry Works, Inc to generate auxiliary power via harvesting engine cooling and exhaust heat loss from heavy duty vehicles. The objective of this research is to evaluate the two phase cooling system through engine dynamometer testing and obtain initial test data for the development of the waste heat recovery system. Engine dynamometer experimentation for evaluating two phase cooling has been conducted using a Perkins diesel engine. During the two phase cooling phase, the coolant temperature showed less than 1 °C variation in the cooling path and the cylinder head temperature was more uniform than that of single phase cooling. As the saturated vapor pressure increases during two phase cooling, the cylinder head and coolant temperatures also increase. Thus, the maximum pressure of the saturated vapor in the two phase cooling is limited by allowable cylinder head temperature that is determined by cylinder head distortion, abnormal combustion, exhaust emissions, etc. The water coolant mixed with trifluoroethanol showed lower cylinder head temperature than pure water coolant at higher vapor pressure of the coolant. Based on the measured values in the engine dynamometer experiment, the potential power output of the proposed waste heat recovery system under the same engine operating conditions in this study ranges from 0.47 KW ~ 1.05 KW.

INTRODUCTION

During the last several decades internal combustion engine technology has achieved significant progress in reducing fuel consumption and exhaust emissions. In particular, strict emission regulation made it possible to reduce exhaust emissions of modern cars to less than 1% of emissions from pre-emission controlled vehicles of 1960s. Fuel economy of modern cars has made a great improvement and various technologies have been applied for reducing fuel consumption in the gasoline and diesel engines. However, even high efficiency modern engines have only 25 ~ 50% thermal efficiency and the remaining 50 ~ 85% of low heating values of the fuel are dissipating into the environment as a form of heat transfer and exhaust gas enthalpy. Several innovative cooling and exhaust heat recovery systems have been introduced to reduce cooling loss and regenerate the power by recovering the waste heat. Nucleate boiling cooling, precision and intelligent cooling, split and reverse cooling, etc are some examples that may optimize the cooling system for reducing cost and cooling loss [1, 2, 3]. Several different thermoelectric systems also have been proposed and tested for generating power via waste heat recovery [4]. Thermoelectrically generated power may displace the conventional alternator and provide additional electric power for the vehicle. In particular, as more vehicles are equipped with hybrid electric power systems, additionally generated power from waste heat recovery may provide additional charging to a hybrid battery pack. However, power generation via the thermoelectric process is still expensive and has low power conversion efficiency with a limited operating temperature window.

Recently Henry Works, Inc. has invented a new technology that may generate additional power in the conventional internal combustion engine using two phase cooling and exhaust gas enthalpy. Figure 1 shows the overall schematic of exhaust heat co-generation system developed by Henry Works, Inc.

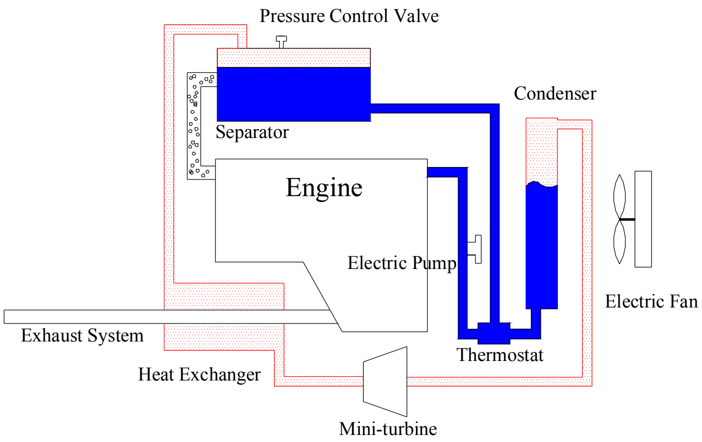

Figure 1. Schematic diagram of the proposed waste heat recovery system.

The main idea of the proposed system is to provide extra power in the vehicle using moderate temperature and pressure steam generated from two phase cooling and super-heated by an exhaust gas heat exchanger. The proposed system adopted nucleate two phase cooling concept for engine cooling and steam generation. While the engine is running liquid phase during the cold start and warming up phase, the coolant liquid becomes the boiling phase and saturated steam is generated at medium and high load conditions. The separator in Figure 1 separates the mixture of liquid and vapor generated in the boiling phase and only the liquid cooling water returns to the engine via an electric coolant pump. The saturated vapor separated in the separator is sent to a heat exchanger and superheated by the heat transferred from exhaust gases. The superheated vapor is expanded in the mini-turbine and generates the electric power for the vehicle. The saturated fluid at the exit of the turbine turns into liquids at the condenser. The combinatory control of electric water pump and thermostat may achieve precise control of the liquid coolant flow rate to optimize the cooling load and maximize steam generation. The advantage of the proposed system is to gain extra power from both engine cooling loss and exhaust enthalpy with high efficiency and low cost. Nucleate boiling engine cooling systems have promising characteristics compared to traditional cooling systems. Figure 2 presents typical heat transfer rate for water boiling. Once boiling starts at points A, the boiling can be categorized into three different regions. Nucleate boiling exists between A and C. In nucleate boiling region, isolate bubbles or jets form and separate from the surface. Heat transfer rates and convection coefficients become very high due to increased fluid mixing and evaporation. Two phase boiling passing C region undergoes transition to film boiling. Unstable region between C and D is termed transition boiling and oscillates between film and nucleate boiling. Film boiling exists after point D. At film boiling region, the surface is completely covered by a water vapor film and as the temperature increases, the surface condition rapidly changes into burnout conditions.

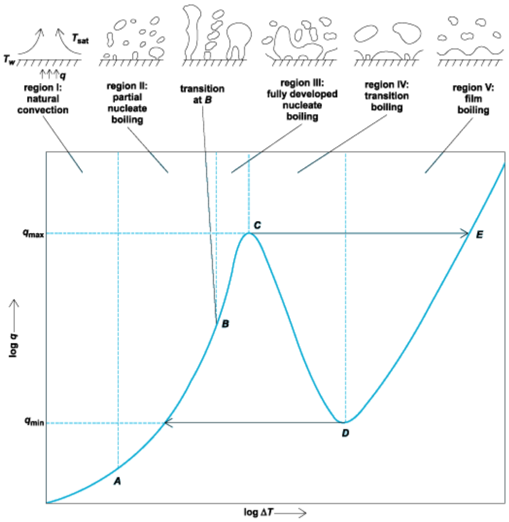

Figure 2. Boiling Curve indicating Heat Flux Change

Since nucleate boiling attains high heat flux during phase change and the temperature variation of the system is minimized, nucleate boiling has been an attractive design choice for spacecraft and planetary thermal control analysis and various design concepts of nucleate cooling for spacecraft has been proposed and tested [5, 6]. However, little research and application of nucleate boiling for the internal combustion engine have been reported although the vehicle or test rig experimental results using nucleate boiling cooling have been reported [7, 8, 9]. Therefore, the objective of this study is to verify a two phase cooling system in the diesel engine through engine dynamometer testing and evaluate the feasibility of the proposed waste heat recovery system shown in Figure 1.

EXPERIMENTAL SETUP AND TEST CONDITION

Engine dynamometer tests of this research have been conducted to verify and evaluate the feasibility of nucleate boiling engine cooling system in the waste heat recovery system proposed by Henry Works, Inc. Figures 3 and 4 present the configuration and photo of the engine test setup installed on the dynamometer for this research.

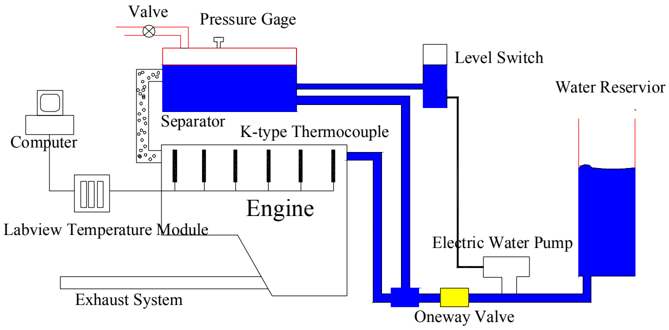

Figure 3. The schematic diagram of engine dynamometer setup for nucleate boiling cooling testing

Figure 4. Engine test setup on the dynamometer

The test setup in Figure 3 is composed of a separator, liquid recirculation system and a temperature measurement system. Two phase flows exiting in the cooling path of the engine are separated into vapor and liquid at the separator and the liquid returns to the engine. The separated vapor in this study is vented to outside and the steam system is open in this study. Since the cooling water circulates through the engine using the mechanical water pump of the engine, the flow rate of the cooling water is not controlled over engine operating conditions. The level switch measures the liquid level in the separator and once the liquid water level is below a pre-defined set position, the level switch turns on and operates an electric motor to pump up the required water from the reservoir. The temperature measurement system has six K-type thermocouples and Labview data acquisition system. Six K-type thermocouples installed in the cylinder head measure metal and water temperatures of the cylinder head. Two of the thermocouples measure inlet and exit temperatures of the cooling water and the rest of the thermocouples are installed close to the combustion chamber to measure the metal temperature of the cylinder head. Figure 5 shows the location of thermocouples installed in the cylinder head.

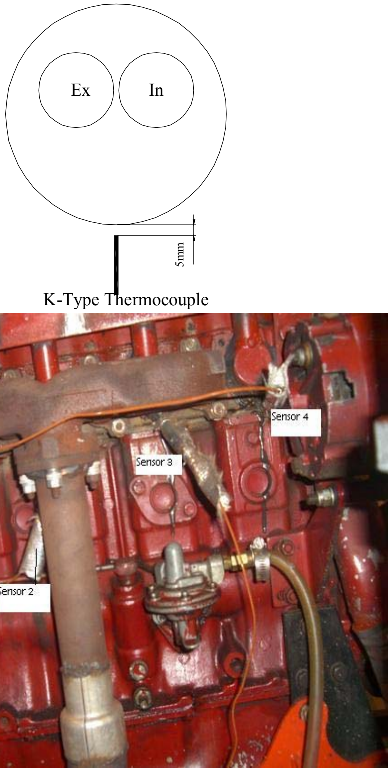

Figure 5. Thermocouples installed in the cylinder head

The test engine is a Perkins in-line 4 cylinder engine (Perkins 4-154). Table 1 indicates the specification of the test engine.

Engine name	Perkins 4.154 diesel
Combustion	Indirect Injection
Number of cylinders	4
Bore (inch)	3.5
Stroke (inch)	16
Cubic capacity (cc)	2522

Table 1. Test Engine Specification.

For this experiment, two different coolants have been used: 100% water and water mixted with trifluoroethanol. Trifluoroethanol is completely miscible with water and due to a unique combination of physical and thermodynamic properties, mixtures of TFE and water can be used as working fluids for Rankine cycle heat engines. The thermal efficiency of a cycle using Fluorinols is substantially higher than the equivalent steam cycle at typical waste heat temperatures. Fluorinols also have desirable turbine expansion characteristics. Other properties of Fluorinols that make them good working fluids are thermal stability, low freezing point, no fire point and compatibility with common metals, elastomers and lubricants. Binary mixture fluids behave different in compositions for the liquid and vapor phases in the two phase region. Azeotrope is defined as the binary mixture whose equilibrium vapor phase has the same composition as that of the liquid phase. At this composition, the binary mixture boils at constant pressure and temperature just like a pure liquid. The boiling point at the azeotropic composition is lower than that of the lower boiling component, for a positive azeotropic binary mixture. Trifluoroethanol (TFE) and its aqueous solutions have been used as working fluids for many years due to their high decomposition temperature. TFE and water (fluorinol) form an azeotropic binary mixture at the composition with 80-mol% TFE and 20-mol% water. At other compositions, fluorinol acts as an azeotrope. The binary mixture at the above mentioned composition is chosen to be an ideal working fluid for the present system.

EXPERIMENTAL RESULTS

Tests have been conducted at four different operating conditions: 1500rpm/40ft lb, 1500rpm/85ft lb, 2000 rpm /40 ft lb, 2000 rpm / 90ft lb. At each operating condition, conventional and two phase cooling have been applied with different coolants. Figure 6 presents the cooling water temperatures at inlet and exit of cooling path. Under single phase cooling mode, •T of coolant is around 10°C. However, as two phase cooling starts, the temperature difference becomes less than 1°C. That is, under two phase cooling conditions, the coolant temperature is almost constant and temperature distributions through the cylinder head are uniform and undergo less thermal stress. Figures 7 and 8 represent the measured cylinder head temperatures at 1500 and 2000 rpm. Solid lines represent middle loads and dotted lines are for high loads. In all tested conditions, single phase cooling showed higher variations of the metal temperature than that of the two phase cooling. At 1500 rpm and middle load condition, metal temperature of single phase cooling is lower than that of two phase cooling at the same condition. However, as the load becomes high, the metal temperature of single phase cooling is higher than that of two phase cooling at the atmospheric pressure. This means that at higher engine load, nucleate boiling becomes more violent and heat transfer rate is higher than that of single phase cooling. However, as we increase the saturated vapor pressure two phase cooling higher than the atmospheric pressure, the metal temperature of two phase cooling becomes higher than that of single phase cooling due to the high saturated water temperature. The temperature variations of cylinder heat at 2000 rpm show the characteristics of the phase change cooling at 1500 rpm. At high load, high speed, and higher pressure of two phase cooling, the maximum metal temperature approached almost 145°C.

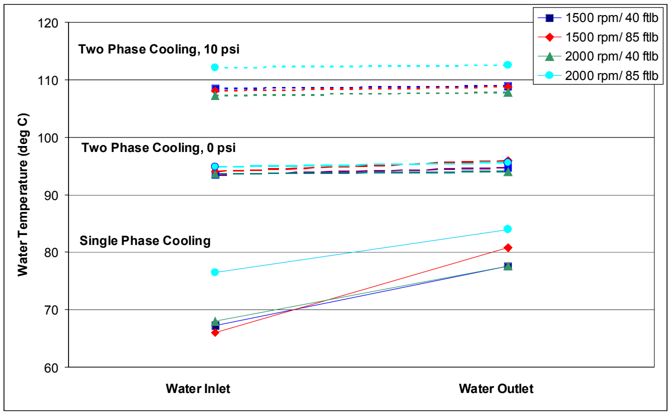

Figure 6. Water temperatures at different cooling conditions.

In this experiment, since the coolant was circulated by a mechanical water pump, the mass flow and heat transfer rate are dependent on the engine speed and cooling methods. Thus, metal temperatures have changed as the engine speed and cooling method are changing. In the four operating conditions, two phase cooling showed better potential for an engine cooling method than the conventional single phase cooling method. Water and metal temperatures under two phase cooling condition are more uniform and stable than those of single phase cooling. Since the metal and water temperature is uniform and stable, it is possible to control the coolant temperature higher than that of single phase cooling. The higher coolant temperature means less cooling loss and better fuel economy. However, as the saturated pressure of the coolant is increased, the coolant and metal temperatures under two phase cooling are also going up. When using the water for two phase cooling, the pressure of the coolant is limited by the metal temperature of the cylinder head. In particular, for gasoline engines, higher metal temperatures mean better chance of knocking. Thus, because of the high saturation temperature of the water, it is hard to use water as a two phase coolant for generating high pressure vapor. For this issue, we tested trifluoroethanol as an alternative coolant for the water. Figure 9 shows the measured metal temperature using mixture of water and trifluoroethanol under different vapor pressures. The data in Figure 9 was measured at two different speeds and 85 ft/lb torque. As TFE mixes with the water, the metal temperature is going down lower than that of pure cooling water. Therefore, when two phase cooling is used to generate power using exhaust heat recovery as shown in Figure 1, pure TFE or a TFE mixture with water is better than pure water to generate the power via running a mini-turbine.

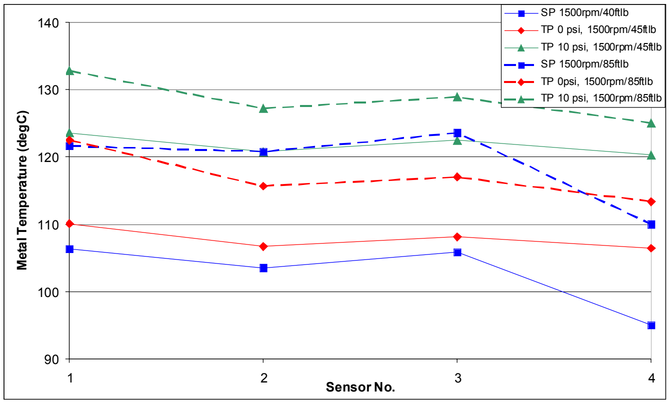

Figure 7. Metal temperatures at 1500 rpm and different cooling conditions

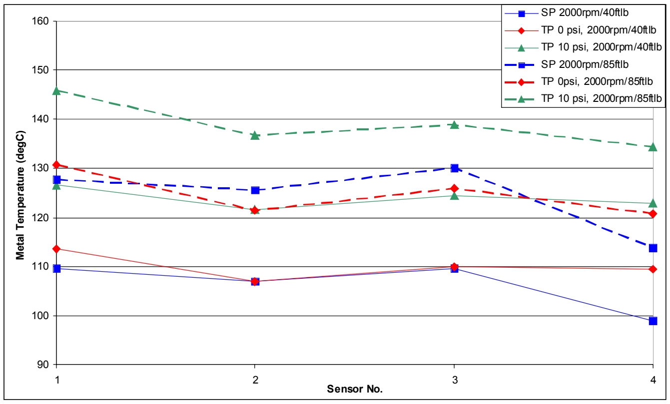

Figure 8. Metal temperature at 2000 rpm and different cooling conditions

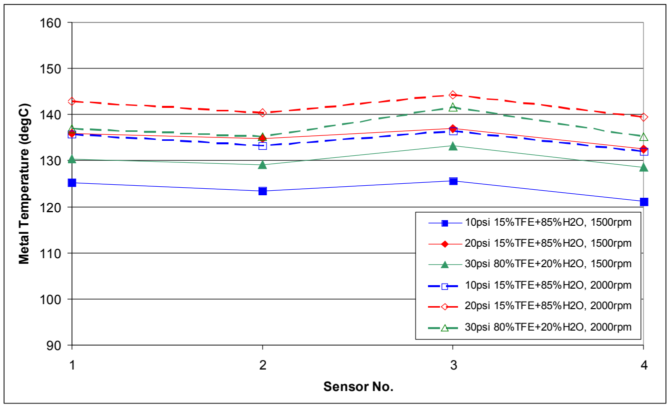

Figure 9. Metal temperature using water and trifluoroethanol mixture

WASTE HEAT GENERATION SYSTEM

The experimental results of this research show that two phase cooling system is efficient for engine cooling and generating the steam. Although the proposed waste heat regeneration system in Figure 1 has not been tested in this study, we may calculate the power generated from the system proposed in Figure 1. The amount of the steam generated in the experiment may be calculated from consumed water during the experiment. The amount of water evaporated during the experiment was measured for 20 minutes and shown in Table 2.

Gallons of H_2O used	Speed(RPM)	Torque (Lb-Ft)
1	1500	40
2. 27	1500	85
1.72	2000	40
3.3	2000	85

Table 2. The amount of water consumed for 20 minutes

For the calculation of net power output of the proposed system using the measured in this research, the efficiency of the turbine in Figure 1 was set at 70%. Table 3 is simple calculation result from waste heat recovery system.

Steam power

speed rpm	Load ftlb	Flow rate kg/s	Power kW
1500	40	0.00315	8.53
1500	85	0.00715	19.35
2000	40	0.00542	14.61
2000	85	0.01039	28.14

Exhaust gas power

speed rpm	Load ftlb	Ex. In°C	•T °C	Cp kJ/kgK	r kg/m3	Mdot kg/s	Power kW
1500	40	300	200	1.04	0.6329	0.0199	2.08
1500	85	400	300	1.063	0.5356	0.0168	1.8
2000	40	400	300	1.063	0.5356	0.0225	2.4
2000	85	500	400	1.087	0.4643	0.0195	2.12

Power out from turbine

speed rpm	Power kW	Power kW	Total Power kW	Net Power Out kW
1500	8.53	2.08	10.61	0.47
1500	19.35	1.8	21.15	0.75
2000	14.61	2.4	17.01	0.68
2000	28.14	2.12	30.26	1.05

Table 3. Waste heat regeneration output calculation

In order to calculate the power from the heat exchanger in Figure 1, the exhaust gas was assumed to be ideal gas and the temperature difference of exhaust gases in the heat exchanger was set at 100°C. If the temperature difference increases, then higher power from exhaust gases can be used for superheating the saturated steam. However, as the temperature decreases, the exhaust temperature at the exit of heat exchanger decreases, which may cause a problem to the efficiency of an after treatment system. From Table

3, the possible power output via waste heat recovery system shown in Figure 1 ranges from 0.47 kW ~ 1.05 kW when using the engine operating condition in this paper. This power output is available in addition to the power output of the engine.

CONCLUSION

A two phase cooling system for a waste heat recovery system has been tested and evaluated via engine dynamometer experiments using a Perkins diesel engine. During the two phase cooling phase, the variation of coolant temperature was less than 1 °C and the cylinder head temperature has shown to be more uniform than that of single phase cooling. As the saturated vapor pressure increases during two phase cooling, the cylinder head and coolant temperatures are also increased. Thus, the maximum pressure of the saturated vapor in two phase cooling is limited by allowable cylinder head temperature that is determined by cylinder head distortion, abnormal combustion, exhaust emissions, etc. The water coolant mixed with trifluoroethanol showed lower cylinder head temperatures than the pure water coolant. Based on the measured values in the engine dynamometer experiment, the potential power output of the proposed waste heat recovery system was calculated. The power output using waste heat recovery under the same engine operating conditions ranges from 0.47 KW ~ 1.05 KW.

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