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Performance enhancement of heat recovery from engine exhaust gas using corona wind

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ABSTRACT

This study develops a new type of heat exchanger with tungsten wires to produce a corona wind. Experimental data are presented for the velocity and temperature of the corona flow from wires to parallel electrodes with respect to the applied voltage and power. Additionally, a gas engine power generation system is manufactured, and its power generation efficiency is tested according to the fuel gas volume fraction between methane and carbon dioxide. Furthermore, an exhaust gas heat recovery system is fabricated using the proposed heat exchanger. A prototype of the corona wind heat exchanger is manufactured, and its enhanced heat recovery efficiency is tested with the gas engine. The corona wind heat exchanger operates well under the available exhaust gas conditions; it increases the temperature of 1 L/min water flow by 45 °C by recovering 2 kW of heat energy from the exhaust gas. The total power production efficiency was increased from 29% to 47%. The results confirm that the proposed corona wind heat exchanger can be applied to the gas engines to greatly enhance their heat recovery efficiency.

1. Introduction

In recent years, biogas has become an important source of renewable energy. It can be produced from organic waste such as sewage sludge, municipal solid waste, agricultural wastes, and energy crops. It consists of methane (50–60%), carbon dioxide (40–50%), and some minor constituents such as hydrogen sulfide and water. Biogas can be used instead of fossil fuels in internal combustion engines to generate electric power, thereby reducing greenhouse gas emissions. The impact of biogas engine emissions on the real industry and the overview of the conversion technologies have been investigated by Benato et al. [1].

Exhaust gas, mainly comprising carbon dioxide, is produced from engines at temperatures of up to 300 °C [2]. The emission of such hot gases not only wastes energy but also leads to thermal pollution of the environment. Thus, many studies have tried to develop heat recovery systems that can exploit the high temperature of exhaust gas from the power generation engines. Dumont et al. [3] most recently, investigated the thermo-economic optimization of an organic rankine cycle waste heat recovery unit for a biogas power plant. Lazaroiu et al. [4] suggested solutions for energy recovery of animal waste from leather industry. And, Hosseini et al. [5] analyzed the thermodynamic assessment of integrated biogas-based micro-power generation system. In fact, 60–70% of the primary energy is lost as waste heat; in internal combustion engines, ~33% is lost in exhaust gas [6]. Therefore, combined heat and power units that can perform multiple roles efficiently and safely offer an important mechanism for energy cascade utilization in power generation engine system.

The heat exchanger is the main component used for heat recovery; it is used to transfer heat between hot and cold fluids. Many studies have tried to improve heat transfer efficiency of the heat exchanger performance in an internal combustion engine. Plate-type[7,8] and shell and tube [9,10] are most commonly used heat exchanger for the waste heat recovery in a compression-ignition engine with rated power of 4 to 6 kW brake horse power(BHP). Recently, the concentric-type cell and tube heat exchanger [11] with transitory thermal storage has been also applied to diesel engine with rated power of 7.4 kW for exhaust gas heat recovery. These results indicated that the proposed heat exchangers normally show a heat exchange efficiency between heated air and cold water by 75–80% and usually it enhanced 6–15% of electric power production rate by heat recover.

Other types of heat exchangers using shape-memory alloys [12] and rod baffles [13] have also been developed. Currently, new materials and technologies are being applied to heat exchangers. Chen et al. [14] applied a scraped-surface heat exchanger on waste-heat recovery from slurries. Tian et al. [15] proposed a new type of heat exchanger called the gravity heat pipe. Wang et al. [8] enhanced the performance of a

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Nomenclature

C_{CH4}	specific heat of methane at constant pressure [kJ/kg·°C]
C_p	specific heat of water at constant pressure [kJ/kg·°C]
D	ion diffusivity coefficient
D_h	hydraulic diameter [m]
E	electric field intensity [V/m]
E_R	recovered power [kW]
E_r	rate of energy recovery [%]
E_{CH4}	heating value of methane gas [kW]
E_{H2O}	calorie of water [kJ]
E_{gas}	calorie of exhaust gas [kJ]
E_{loss}	heat energy loss [kW]
E_{engine}	electric power production from engine [kW]
H_r	rate of heat loss [%]
H	heat transfer coefficient [W/m²k]
H_v	amount of vortex heat exchange [mcal/s]
h_{tot}	total enthalpy
Q	volume flow rate [L/min]
Q_{CH4}	volume flow rate of methane gas [L/min]
Q_{H2O}	volume flow rate of water [L/min]
P_{mech}	mechanical conversion energy of corona wind [W]
P_{elec}	consumed power for corona wind [W]
P_t	total power production [kW]
Re	Reynolds number
T_s	surface temperature [°C]
T_∞	ambient temperature [°C]
U	velocity of air flow [m/s]
V_c	onset voltage [kV]
f_e	Coulomb force [N]
h	heat transfer coefficient [W/m²·K]
h_e	enthalpy [kcal]
h_{tot}	total enthalpy [kcal]
J	current density [A/m²]
K	ion mobility
VFC	volume fraction of carbon dioxide
p	pressure [Pa]
q	space charge [C]
q''	heat flux [W/m²]
ϵ	dielectric permittivity
λ	thermal conductivity [W/m·K]
μ	coefficient of viscosity [N·s/m²]
ρ	density of air [g/cm³]
ρ_{CH4}	density of methane [g/cm³]
ρ_{H2O}	density of water [g/cm³]
τ	friction [N]
η	viscosity of air
η_{engine}	electric power production efficiency of engine [%]
$\eta_{exchanger}$	heat transfer efficiency of heat exchanger [%]
η_{corona}	energy conversion efficiency of corona wind [%]
η_t	total energy recovery efficiency [%]

thermoelectric waste heat recovery system by using metal foam inserts. Ma et al. [16] suggested the optimum operation conditions for a heat-pipe-assisted heat exchanger used for industrial waste heat recovery. The results indicated the proposed new type of heat exchanger normally improved the heat transfer rate by 6–8% for 4–6 kW of heating power.

In this study, we suggest the use of corona wind for heat recovery from exhaust gas. Corona wind is an emerging technology that can use electro-fluid energy conversion, where bulk air motion is induced by a corona discharge between electrodes such as a wire and a plate. Many studies have exploited corona wind for enhancing heat transfer. We consider that applying corona wind in a heat recovery system affords many advantages for heat transfer. First, corona wind generally consumes very little power, and therefore, it does not cause any extra reduction in electric power generation efficiency of a gas engine. Moreover, the pressure drop induced by the expansion surface in heat exchangers, which has been a most serious problem, can be solved by using corona wind because it induces a uniform surface flow on heat exchanger fins by accelerating the space charges and reducing viscous effects. Therefore, the local Reynolds number increases at the fins, in turn increasing the total heat transfer performance during heat recovery. Finally, corona discharges can decompose carbon dioxide and purify exhaust gas, which is a necessity for realizing ecofriendly gas engines.

Many studies have investigated corona discharge for improving the heat transfer performance of heat exchangers. Several studies have demonstrated the superior heat transfer rates of ionic wind and its increased heat transfer coefficient. Rashkovan et al. [17] optimized an electric blower using corona wind and confirmed its superior heat transfer performance compared to a heat sink. Wang et al. [18] experimentally investigated the cooling performance of ionic wind using a pin for a high-power LED. Huang et al. [19] investigated the influence of electrohydrodynamic (EHD) flow on heat transfer for a plate fin heat sink subjected to needle-arrayed electrodes. Corona discharge is also known to decompose carbon dioxide and sulfur oxides present in exhaust gas [20]. However, the application of corona wind in heat exchangers for exhaust gas heat recovery in a gas engines has not been reported previously. Based on our recent findings [21,22], in this study, we propose a corona wind heat exchanger with wire and plate electrodes for heat recovery from exhaust gas. Corona wind heat exchangers for product and manufacturing engineering have thus far suffered from problems such as the providing and controlling of a high voltage for operation, the degradation of electrodes over time, and minimizing ozone production, which are very practical hurdles for their commercialization. Nevertheless, we believe that a corona wind heat recovery system shows strong potential for energy generation engineering applications. Thus, attempts should be made to study and demonstrate real products. Accordingly, this study presents both fundamental studies of corona wind and applications by demonstrating a real product for use in heat exchangers.

In this study, a power generation gas engine system is equipped with the novel heat exchanger and the power generation characteristics according to the fuel gas composition are studied. Additionally, a heat recovery system is fabricated for hot water, and its heat transfer characteristics are tested using the gas engine. The generated electric power is measured, and the energy recovery efficiency is estimated with respect to the performance of the gas engine and calorie of hot water recovered by the heat exchanger using corona wind. A comparison test has been performed for the real heat exchanger product using corona wind and shell and tube, in terms of its enhanced heat transfer performance by measuring the volume reduction and heat recovery efficiency.

2. Theoretical background

If an electric field is applied between a wire (a discharge electrode) and a plate electrode (collecting electrodes), then a corona discharge occurs at the wire. This local discharge ionizes air molecules into ions and electrons. Next, the charged ions and electrons move in opposite directions as space charges according to their polarity. During this movement, heavy ions impact air molecules and transfer inertia. Through collisions between accelerated ions and air molecules, a flow can be generated; this is called an ionic wind or corona wind.

The electric field intensity between electrodes has the most dominant effect on the performance of corona wind. The electric field E is