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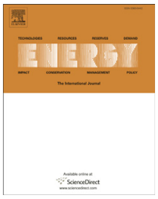

Thermal modeling of a novel thermosyphonic waste heat absorption system for internal combustion engines

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A B S T R A C T

This paper investigates a thermal system that absorbs waste heat from an internal combustion (IC) engine in order to raise the temperature of a working fluid to a saturated state using thermosyphonic flow, non-intrusive of the engine operations. The absorbed heat is rejected to an enclosed space, suitable for in-transit drying. The thermal system comprises a cross-flow heat exchanger connected to a radiator which preheats the working fluid from an insulated (storage) tank. The preheated fluid flows through a radiant heat absorber which absorbs radiant heat from the exhaust manifold. To ensure that the system efficiently performs, a temperature differential is maintained by the heated space while the fluid is cyclically delivered to the tank. The system's operations are described using a novel flow cycle, and the results indicate a significant heat recovery potential.

1. Introduction

Typically an internal combustion engine converts less than 42% of the chemical exergy available in the fuel into mechanical energy with the remainder converted to thermal energy which is lost to the environment: there are two pathways for utilizing the chemical exergy of the fuel [1], the first involves minimizing exergy destruction in the combustion process while the second involves tapping the exhaust exergy to obtain further improvements in the thermal efficiency of the engine. Besides the heat energy converted into useful work to deliver mechanical power in IC engines, there is a considerable amount of heat losses in the engines which affect the fuel utilization efficiency.

A good number of waste heat recovery devices operate on the basis of the Rankine cycle [1,2]. A, methodical approach for employing a waste heat recovery device in truck vehicles based on the Rankine cycle dates back to the early 1970s.A research investigation conducted by Parimal and Doyle [2], Dibella et al. [3] and Doyle et al. [4], on an Organic Rankine Cycle System (ORCS) coupled to a Mack truck diesel engine resulted in an improvement in the brake specific fuel consumption (BSFC). Recently, Ghazikaki et al. [5] investigated the effect of exhaust cooling system on exergy recovery in a direct ignition diesel engine, and obtained a BSFC reduction of 5–15% in different load and speed conditions. Similar research programs have been undertaken with some improvements in several ORCS [6,7]. Khatita et al. [8] conducted parametric analysis and optimization study on an ORC system for power generation, with optimal conditions for operation. In addition, Briggs et al. [9] conducted a study on the effects of turbogeneration on an electric hybrid bus, and developed a one-dimensional simulation model, which resulted to considerable reduction in the fuel consumption over a drive cycle. With the exception of turbocompounding, most existing solutions for the recovery of exhaust heat losses utilize a heat exchanger to extract the heat [1,6], such heat exchangers must have areas that match the thermal duty, and this significantly affect vehicle weight. Some other designs are essentially suitable for industrial use [1,7], while others for thermoelectric applications [10]. These units are however often bulky and do not scale with small engine compartments to warrant their use.

Considerable improvement in diesel engine's BSFC can be achieved by utilization of the exhaust energy [6]. Heat engines, due to high combustion temperature and pressure, can be adapted to efficient energy technologies. As research interest into waste energy and scavenging technologies gathers momentum as a result

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Nomenclature

A	area (m^2)
C	heat capacity rate (J/s K)
C_p	specific heat capacity (J/kg K)
C_r	heat capacity ratio
D_e	equivalent diameter (m)
E_f	total energy in fuel (J)
E_t	total energy absorbed by cold fluid (J)
f	fin
F	fanning friction factor
F_B	buoyant force (J)
g_c	proportionality constant (kg m/N s^2)
h	convective heat transfer coefficient (W/m^2 K)
h^+	vertical length of the tank (m)
I_{sur}	radiation intensity (W/m^2)
k	thermal conductivity (W/m K)
L	flow length (m)
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_f$	mass flow rate of fuel (kg/s)
N	number of passes
Nu	Nusselt number
Pr	Prandtl number
q	heat flux (W/m^2)
Q	heat transfer rate (W)
Q_u	useful power (W)
v_t	tank volume (m^3)
q_{rad}	radiation heat flux (W/m^2)
$\bar{q}_{rad}$	average value of q_{rad} (W/m^2)
R	resistance (m^2 K/W)
Re	Reynolds number (m)
T	temperature (K)
θ_T	dimensionless temperature
T_0	reference temperature
U_p	overall conductance (W/m^2 K)
U	overall conductance (W/m^2 K)
U_p	overall conductance for the absorber (W/m^2 K)
V	velocity (m/s)
Ω	fluid volume in tank (m3)
ΔP	pressure drop (Pa)
ρ	density (kg/m^3)
ρ_b	density of fluid at bottom of tank (kg/m^3)
ρ_t	density of fluid at top of tank (kg/m^3)
δ	thickness (m)
μ	dynamic viscosity (Ns/m^2)
μ_w	the dynamic viscosity (wall quantity) (Ns/m^2)
σ	Stefan–Boltzmann constant (W/m^2 K^4)
u^*	dimensionless gas speed (m/s)
y^+	dimensionless distance
G	source in energy equation
ϕ_{us}	dimensionless unsteady temperature
τ	dimensionless time
ν	gas speed (m/s)
γ	adiabatic coefficient

Subscripts

c	cold
f	fin
me	mean
ε_{pt}	particle emissivity
h	hot
H	height
W	width
L	length
min	minimum
max	maximum
i	h, c
in	inlet
out	out
a	ambient
ex	exhaust
t	tube
Tot	total
rad	radiation
∞	free stream
m	manifold
p	plate
rad	radiation
abs	absorber
pre	preheater
c_1	cover 1
c_2	cover 2
s	scale
w	wall
t	tube
pt	particle
tot	total

of rising fuel costs, specific designs of heat recovery systems which are relatively simple and non-intrusive are rarely being investigated.

Globally, there are a billion cars [11] with a conservative estimate of about 200 GW of heat losses. These losses can be harnessed to meet some useful thermal applications. Since most of the energy in the fuel is lost as heat, capturing these losses to heat a working fluid to a saturated state (for in-transit drying in food-purveying vehicles, and commercial hot water applications in remote locations where grid power is unavailable) can provide an increase in the fuel conversion efficiency, as well as mitigate environmental impacts arising from the emission of greenhouse gases which arguably can impact the pattern of fuel consumption globally, as well as the environment. In this work, a novel approach for tapping waste heat from an IC engine on the basis of thermosyphonic flow mechanism is studied. It differs from other heat recovery units in its non-intrusive operational design, retrofittability and placement. The system comprises a cross-flow heat exchanger connected to a radiator for preheating the working fluid from an insulated (storage) tank. The preheated fluid flows through a radiant heat absorber which absorbs radiant heat from the exhaust manifold. The absorbed heat can be utilized in a variety of thermal applications, thereby increasing the engine energy efficiency. The system and its operations – for which a patent is pending – are subsequently described.

2. Methodology of design

Descriptively, the present design consists of a two-stage heating process. In the first, waste heat from the engine jacket is used to preheat the working fluid employing a cross-flow heat exchanger (1) connected to a radiator (2), (Fig. 1). Successively, the preheated fluid is passed through a specially designed radiant heat absorber (RHA) (3), consisting of a selectively coated absorber, transparent