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Energy and exergy comparisons of water based optimum brines as coolants for rectangular fin automotive radiator

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ABSTRACT

The present study focuses on the energetic and exergetic analyses of rectangular fin and flat tube automotive radiator using water, EG, PG and their brines. Effects of various operating parameters on heat transfer rate, effectiveness, pumping power, performance index as well as entropy generation, entropy generation number, irreversibility and second law efficiency have been studied. Study shows that the optimum (25% PG) brine solution yields energetic and exergetic performance similar to that of water and significantly better compared to 25% ethylene glycol brine. Optimum brine solution of propylene glycol yields highest effectiveness, performance index and heat transfer with lowest pumping power. Both 25% propylene glycol brine and water yield 50% higher effectiveness and 7% higher second law efficiency compared to 25% ethylene glycol brine. Optimum propylene glycol brine may yield reduction in radiator cost, engine fuel consumption and environmental benefit. This study represents 25% PG brine as much better coolant than conventional EG brine.

1. Introduction

Many technical developments have been introduced to meet the requirements on low fuel consumption and CO_2 emission in vehicles. Concerning the energy distribution in the vehicle, around 30% of the total energy input to engine is brought away by the coolant of the engine cooling system. If one could optimize the energy wasted through the coolant, the fuel consumption and the CO_2 emission could be reduced. If the engine cooling system cannot bring away the heat quickly, the engine working temperature will increase. More fuel will be consumed and the life time of the engine will be reduced due to the high working temperature in the engine. Contrarily, a good engine cooling system can reduce the time of the engine start and warm up processes, in which the engine reaches its optimal working temperature [1]. A lot of hydrocarbon (HC) and carbon monoxide (CO) are produced during the starting and warming up period [2]. On the other hand, the compact radiator design is needed to reduce the vehicle frontal area and hence to reduce the drag. Hence, compact, efficient and optimum radiator design has become a backbone of vehicle development.

There are basically two methods to increase the thermal performance of radiator [3]. One is the passive technique, which includes special surface geometries and fluid additives and another is the active technique, in which the external power is required. However, due to the cost, noise, safety or reliability being concerned, the passive techniques are more popular. The passive techniques include coated surfaces, rough surfaces, extended surfaces, displaced inserts, swirl flow, coiled tubes, surface tension, additives for liquids, and additives for gas. The extended surfaces will lead to high compactness in heat exchangers, which is favourable for the vehicle industries [4,5]. The historical development of fin (extended surface) patterns can divided in three stages [6]. First generation pattern was plain and wavy fin geometry. Second generation had interrupted surfaces features which enhanced heat transfer mechanism like boundary restarting, wake management and flow destabilization. The third generation with the enhanced surfaces employ longitudinal vortex generation that provided swirling motion to the flow field. Parametric studies on automotive radiators showed the significant effects of fin geometrical parameters the overall heat transfer coefficient [7]. Many recent experimental studies have also investigated the effects of various fin geometries and configurations, and operating parameters on the heat transfer and pressure drop characteristics of fin and tube heat exchangers (radiators) and developed the correlations for predicting Nusselt Number and friction factor [8–13].

Improved thermophysical properties of coolant in vehicle thermal management are desirable not only for performance also for operation and safety. Water is widely used as coolant due to its

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Nomenclature

A	heat transfer area (m^2)
C	heat capacity rate (W/K)
c_p	specific isobaric heat (J/kg K)
C^*	heat capacity ratio
D_h	hydraulic diameter (m)
f	friction factor
G	mass velocity (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
I	irreversibility (W)
k	thermal conductivity (W/m K)
m	mass flow rate (kg/s)
NTU	number of heat transfer units
Nu	Nusselt number
p	pressure (Pa)
P_F	fan power (W)
PI	performance index
P_P	pumping power (W)
Pr	Prandtl number
Q	heat transfer rate (W)
R	gas constant (J/kg K)
Re	Reynolds number
S_{gen}	entropy generation rate (W/K)
T	temperature (K)
T_0	dead state temperature (K)
u	fluid velocity (m/s)
U	overall heat transfer coefficient (W/m^2 K)
V	volume flow rate (m^3/s)
Δp	pressure drop (Pa)
ΔEx	exergy gain or loss rate (W)
η_o	total heat transfer surface effectiveness
η_{II}	second law efficiency
ρ	fluid density (kg/m^3)
ε	heat exchange effectiveness

Subscripts

a	air
f	fluid (coolant)
i	inlet
e	exit

good heat transfer performance and safety. However, various antifreeze liquids have been introduced with water to avoid the operational restriction of pure water. Ethylene glycol (EG) and propylene glycol (PG) are the most preferred antifreeze liquids and comparison is shown in Table 1. Use of both EG and PG with water degrades the heat transfer as well as pressure drop performances, however, EG is better than PG [14,15] and hence the water based EG brine has received wider acceptance as radiator coolant. In 1990s, the nanofluids have been introduced, which has enhanced thermal conductivity [16,17]. Many theoretical and experimental researches on radiator using nanofluids have been carried out and found these new radiator coolants are excellent [18–21]. Recently, the present authors group interesting observed that 25% PG brine can perform similar to water in louvered fin radiator [22] although PG has in-general poor performance than EG. Furthermore, PG is cost competitive, readily available and much less toxic compared to EG [14]. These facts have motivated for further study on other radiators.

This paper presents the energetic and exergetic analyses of rectangular fin and flat tube automotive radiator using 25% propylene glycol and 25% ethylene glycol brine solutions and comparison with water. Effects of various operating parameters on the energetic (heat transfer rate, effectiveness, pumping power and performance index) as well as exergetic (entropy generation, entropy generation number, irreversibility and second law efficiency) performances has been studied as well.

2. Theoretical modelling and simulation

Rectangular fin-tube radiator considered here is cross flow type as, which was taken from model of Maruti 800 car. The core portion of the radiator (Fig. 1) consists of vertical flat coolant tubes and rectangular fins. All the dimensions, as shown in Table 2, have been measured in laboratory. The formulation with various coolants is based on energy and exergy balance including heat transfer and fluid flow effects. The following assumptions have been made for the modeling:

- Steady flow for both air and coolant.
- All the heat rejected from coolant absorbed by air flow through radiator.
- Properties have been taken based on mean fluid temperature.

Air-side heat capacity rate is given by [19]:

$$C_a = \rho_a u_a H_c W_c c_{p,a} \tag{1}$$

Air-side heat transfer coefficient has been calculated by,

$$h_a = Nu_a k_a / D_{h,a} \tag{2}$$

where Nusselt number for air for rectangular fin is given by [19],

$$Nu_a = 0.6648 Re_a^{0.5} Pr_a^{0.33} \tag{3}$$

Now, the coolant-side heat capacity rate is given by,

$$C_f = \rho_f V_f c_{p,f} \tag{4}$$

Coolant-side heat transfer coefficient can be expressed as:

$$h_f = \frac{Nu_f k_f}{D_{h,f}} \tag{5}$$

Nusselt number for turbulent flow of coolant is given by,

$$Nu_f = \frac{(f_f/2) Re_f Pr_f}{1.07 + 12.7\sqrt{f_f/2}\left(Pr_f^{(2/3)} - 1\right)} \tag{6}$$

Table 1
Basic property data of water, ethylene glycol and propylene glycol [22].

Fluids	Freezing point (°C)	Boiling point (°C)	Density (kg/m^3)	Toxicity
Water	0	100	1000	Not toxic
Ethylene glycol	−12.9	187.4	1110	Moderate
Propylene glycol	−59.0	197.3	1033	Low
25% EG brine	−11.0	103.3	1028	–
25% PG brine	−33.1	101.3	1032	–