THERMAL DESIGN OPTIMIZATION AND PERFORMANCE EVALUATION OF HEAT EXCHANGER WITH LOW GRADE ENERGY UTILIZATION

Thesis Submitted in Partial Fulfilment

For the Award of Degree

DOCTOR OF PHILOSOPHY

By

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DECLARATION BY THE CANDIDATE

I, **Vikash Kumar,** certify that the work embodied in this thesis is my own bona fide work carried out by me under the supervision of **Dr. R.R. Sahoo** for a period of 4 years 9 months from December 2017 to September 2022 at IIT (BHU) Varanasi. The material contained in this thesis has not been submitted for the award of any other degree. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any others' work, paragraphs, text, data, results etc. reported in journals, books, magazines, reports, dissertations, theses, etc. or available at websites and have not included them in this thesis and have not cited as my own work.

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List of Symbols

Nomenclatures

A_0	Total surface area (m^2)
A_t	External tube surface area (m^2)
A_{tt}	Area of the twisted tape (m^2)
A_c	Minimum free flow area (m^2)
A_{fin}	Peripheral area of fin (m^2)
A_{fr}	Frontal heat transfer area (m^2)
Al_2O_3	Aluminium oxide
CO	Carbon monoxide
C_p	Specific heat capacity (J/kg. K)
CuO	copper oxide
D_c	fin collar outside diameter (mm)
D_h	hydraulic diameter (mm)
D_i	Internal diameter (mm)
D_o	Outer diameter (mm)
D_p	Perforated diameter (mm)
Dis_{CO_2}	CO_2 discharge (Tonnes/year)
ES	Engine speed (RPM)
Ex	Exergy (W)
ff	friction factor
f_1,f_2,f_3	Correlation parameters for the friction factor
f_{CO_2}	Carbon discharge factor

f_p	Fin pitch (mm)
HC	Hydrocarbon
h_f	Heat transfer coefficient (W/m^2. K)
IRR	Irrevesibility (W)
k	Thermal conductivity (W/m. K)
LCV	Lower calorific value (MJ/kg)
Ld	Applied load (kg)
$\dot{m}$	Mass flow (kg/s)
Nu	Nusselt number
ɵ	wavy angle (radian)
P_d	Waffle height (mm)
P_l	Longitudinal tube pitch (mm)
P_p	Perforated pitch (mm)
P_{pp}	Pumping power (W)
Pr	Prandtl number
P_t	Transverse tube pitch (mm)
Q	Heat transfer (W)
Re	Reynolds number
S_{gen}	Entropy generation (W/K)
SN	Signal to noise
T	Temperature (˚C)
t_i	Insert thickness (mm)
TiO_2	Titanium dioxide
V	Velocity (m/s)

VFR	Volume flow rate (lpm)
W	Width (mm)
X	geometrical parameter
X_f	projected fin pattern length (mm)
Y	Twisted pitch (mm)

Greek symbols

ρ	Density (kg/m^3)
μ	Dynamic viscosity (kg/m-s)
η	Efficiency
α	Fin efficiency
Ψ	Indentation coefficient
Δp	Pressure drop (Pa)
φ	volume fraction

Abbreviation

AFS	Annual fuel saving
AFC	Annual fuel consumption
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CF	Colburn factor
CFD	Computational fluid dynamics

CO_2	Carbon dioxide
CR	Contribution Ratio
DG	Discharge
EDX	Energy-dispersive X-Ray
FR	Friction ratio
GRC	Grey Relational Coefficient
GRG	Grey Relational Grade
HC	Hydrocarbon
HTC	Heat transfer coefficient
HX	Heat exchanger
IEP	Isoelectric point
MEOB	Methyl ester orange blend
MWCNT	Multiwalled carbon nanotube
NO_X	Nitrogen oxides
NR	Nusselt ratio
OTP	Overall thermal performance
OEU	Overall experimental Uncertainty
OPB	Orange peel blend
OPO	Orange peel oil

PEC	Performance evaluation criteria
PHS	Preheating section
PT	Plain tube
PTTI	Perforated twisted turbulator/tape insert
RNG	Renormalization group
SHC	Specific heat capacity
SI	Sustainability index
SNR	Signal to Noise Ratio
TG	Taguchi Grey
THNF	Ternary hybrid nanofluid
TPF	Thermal performance factor
TTI	Twisted Turbulator/tape insert
XRD	X-ray diffraction

Subscripts

a	Air
ai	Air inlet
ao	Air outlet
amb	Ambient
bf	Base fluid
cin	Coolant inlet
ce	Coolant exit

e	Exit
eff	Effective
exp	Experimental
f	Fluid
fi	Fluid inlet
fo	Fluid outlet
fuel	Fuel
gen	Generation
i	Inner
m	Mean
max	Maximum
min	Minimum
nf	Nanofluid
o	Dead state
oc	Operating cost
p	Pump
pp	Pumping power
pre	Predicted
r	Ratio
radiator	Radiator
t	Tape
uh	Unaccounted heat
wph	With preheat

Abstract

Energy utilization is a crucial parameter for the socio-economic growth of a nation. As living standard improves, the energy demand also rises. Modern science has brought forth cutting-edge innovations, forcing the car sector to create more potent engines. The cooling system of the engines needs to be improved to keep up with the innovation. Emergence in modified technologies requires rapid heat removal methods for better performance of the heat exchangers. To overcome this issue, the heat exchanger is optimized to use for practical applications, and for the betterment of the heat exchanger performance, different working fluids and optimized passive device turbulator inserts are used. Also, for practical application, the waste energy of the coolant is used to preheat the prepared blended biodiesel fuel using an intermediate heat exchanger with its effect on the engine performance and energy utilization. The three different compositions of hybrid nanofluids (0.06-0.12%) (v/v) are prepared for utilization as a coolant in the heat exchanger. The better coolant is used in the engine and the waste energy of coolant is utilized for preheating fuel, concurrently. The prepared ternary hybrid nanofluids are found to be stable and nanoparticles are well dispersed for the lower concentration as claimed by the Ultraviolet-visible spectrophotometer. All the nanoparticles obtained to be the spherical shape of size lower than 100nm, obtained using SEM and EDX analysis. The pH of the solution obtained far away from the isoelectric point ensures the fluid is used for practical application. On nanoparticle addition, thermal conductivity, and viscosity increased but the specific heat of the fluid reduced significantly.

In the present study, based on heat exchanger requirement, parametric study for the air-side is considered with larger heat transfer and lower frictional factor as the target response using the Taguchi method. Also, a statistical concept Grey relational analysis is used for combined optimization considering all target responses at one time. Experimental suitable

correlations are used for the 27 orthogonal runs. Investigation revealed the highest 47.06% fin pitch, 37.24% fin pitch, 25.46% air velocity, and 23.9% fin thickness contribution ratio for the target response of friction factor, TPF, heat transfer coefficient, and Colburn factor respectively. GRG gives an optimum set of design parameters for a wavy fin and tube of fin pitch of 3.5mm, the number of tube row 3, waffle height 2.2mm, fin thickness 0.15mm, air velocity 5m/s, longitudinal tube pitch 19.6mm, and transverse tube pitch of 24.8mm, at which TPF is maximum while the friction factor is minimum. Hence, an improved heat transfer performance design of a wavy fin and tube heat exchanger is achieved using the above techniques.

In the subsequent experimental investigation, for thermal improvement, passive inserts of twisted turbulator/tape inserts (TTI), Perforated twisted turbulator/tape inserts (PTTI) are used. In this work, the optimized dimension of wavy fin and tube heat exchanger is used. The energy, Exergy, and Economic sustainability effect of modified inserts with prepared water-based ternary hybrid nanofluid (THNF) are investigated. The 3E's (Energy, Exergo-economic), are investigated with a control flow parameter. Experimental results revealed that turbulator inserts (TTI, PTTI) with nanofluid enhance the thermal and hydraulic performance of the compact air heat exchanger. The turbulator inserts of PTTI and TTI in plain tubes using 0.12% (v/v) of THNF results in the highest 28% and 19% heat transfer, 80% and 50% friction factor, 49.4% and 34.4% exergy change, 17.8%, and 12.7% entropy, and higher sustainability index at lower Reynolds number, respectively. Meanwhile, the turbulator inserts of PTTI and TTI in the tube core require 2.6 and 2.1 times, 2.07 and 1.8 times higher CO_2 discharge and operating cost compared to plain tube. PTTI with 0.12% (v/v) THNF as working fluid and tube insert should be preferred due to its PEC ranges of 1.075-1.04.

To use the perforated twisted turbulator inserts for the application in heat exchanger the exact dimensional and fluid flow selection are investigated. Also in the present investigation, the effect of PTTI based heat exchanger utilizing nanofluid as working fluid undercooling, turbulent flow model has been investigated numerically. Parameters perforated pitches (20mm – 40mm), 0.12%(v/v) THNF at different flow conditions (3800-8150), and perforated diameters (2mm - 4mm) variation effects on fluid outlet temperature, Nusselt ratio, Friction ratio, pressure drop, overall thermal performance, CO_2 discharge, and HX_{OC} have been investigated. This work also focuses on design optimization with three different factors and three levels for higher HTC (Heat transfer coefficient) and minimum pressure drop based on the Taguchi-Grey method. CFD output is used as an input value for statistical analysis. According to the results, PTTI in HX successfully achieved overall heat transfer enhancement in the range of 19.2% to 28.5%, but at the cost of pressure penalty of 126% to 163% higher than the plain tube. Critical Reynolds number 6000, above which PTTI in HX is least suitable for heat transfer enhancement as fluid velocity dominates over heat transfer and 1.7 to 2.5 times higher carbon discharge to the environment and higher HX_{OC}. Preference sets of geometrical and fluid parameters are obtained using Grey analysis. Based on statistical analysis, in the considered levels, a group of parameters to attain higher HTC and minimum pressure drop are lower Reynolds number 3800, the perforated pitch of 20mm, and a perforated diameter of 4mm. These suitable optimized dimensions were used for the experimental investigation.

For practical application, the experimental study investigated the utilization of preheated Methyl ester orange blend, MEOB of D-30%OPB biodiesel (30% Methyl ester and 70% diesel) blended biodiesel as a renewable fuel to the diesel engine. The orange peel methyl ester is a sustainable, renewable, toxic less, alternative fuel produced from the transesterification of orange peel oil. Blended biodiesel and diesel are preheated to a temperature ranging from 30 – 43°C using the heat extracted from the coolant waste from a preheating section (PHS). Coolant energy is dependent upon the engine load. Preheated diesel

and blended biodiesel are tested in a diesel engine at different loading conditions at a fixed speed 1500 RPM to evaluate the engine performance (brake thermal efficiency (BTE), brake specific consumptions (BSFC)), exhaust emissions (HC, NO_X, and CO), and fuel energy distribution. Results are obtained with the engine load variation of different part loads. Results revealed that preheating of fuel causes better fuel spray and combustion characteristics which significantly improves the BTE, and reduces BSFC, HC, and CO emissions with increased CO_2 and NO_X emissions. Optimum performance obtains at 5.6kW load conditions. At 5.6kW loading, with preheating (WPH), BTE of D-30%OPB biodiesel increased by 3.3%, and diesel by 3.2% than unheated fuel. BSFC, HC, and CO emissions of preheated D-30%OPB biodiesel and diesel at 43°C, 5.6kW load conditions are reduced by 7.9% and 8.4%, 3.9% and 5.2%, 3.6%, and 4.4% respectively compared to unheated fuel. Energy utilization revealed a maximum of 6.6% and 6.1% waste energy of coolant is utilized to preheat the D-30%OPB biodiesel and diesel at 5.6kW load conditions, respectively. Therefore, an efficient engine is possible if the waste energy of engine coolant is utilized.