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Numerical study of an exhaust heat recovery system using corrugated tube heat exchanger with twisted tape inserts☆

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ABSTRACT

The purpose of this work is to investigate gas to liquid heat transfer performance of concentric tube heat exchanger with twisted tape inserted corrugated tube and to evaluate its impact on engine performance and economics through heat recovery from the exhaust of a heavy duty diesel generator (120 ekW rated load). This type of heat exchanger is expected to be inexpensive to install and effective in heat transfer and to have minimal effect on exhaust emissions of diesel engines. This type of heat exchanger has been investigated for liquid to liquid heat transfer at low Reynolds number by few investigators, but not for gas to liquid heat transfer. In this paper, a detail of heat transfer performance is investigated through simulations using computer software. The software is first justified by comparing the simulation results with the developed renowned correlations. Simulations are then conducted for concentric tube heat exchanger with different twisted tape configuration for optimal design. The results show that the enhancement in the rate of heat transfer in annularly corrugated tube heat exchanger with twisted tape is about 235.3% and 67.26% when compared with the plain tube and annularly corrugated tube heat exchangers without twisted tapes respectively. Based on optimal results, for a 120 ekW diesel generator, the application of corrugated tube with twisted tape concentric tube heat exchanger can save 2250 gal of fuel, $11,330 of fuel cost annually and expected payback of 1 month. In addition, saving in heating fuel also reduces in CO_2 emission by 23 metric tons a year.

1. Introduction

In Alaska, there are about 180 villages using independent off grid diesel generators for many decades and are not equipped with exhaust heat recovery systems to take advantage of the energy in form of heat contained in the exhaust which is about 1/3 of fuel energy. Even a fraction of heat energy recovered may have a significant effect on heating fuel costs of cold region villages. From village power industry point of view, the major reasons for not installing exhaust heat recovery system is the effect on exhaust emissions and may cause maintenance difficulty resulting from soot accumulation and corrosion. In most of the Alaskan rural villages except in large power plants, maintenance technicians and engineers are not readily available when a maintenance problem rises (especially during winters), the shipping of equipment and traveling are also very expensive for isolated villages in the cold regions.

One of the heat recovery systems which can match the needs is the vertically installed concentric tube heat exchanger with simple structure, which has been tested to capture the exhaust heat on a 120 kW diesel generator and no evidence has been found in emissions and maintenance. The heat exchanger is installed vertically in order to reduce the soot accumulation. The water exiting the engine jacket is further heated in the current heat recovery system and supplied for space heating. The advantages of using jacket water for heat recovery are economical in installation, no additional pumping power required and no extra loop cost.

The purpose of this work is to further improve the effectiveness of heat recovery by using heat augmentation techniques. A literature review has been conducted on concentric tube heat exchangers to determine the most suitable type of heat exchanger for cold region villages with higher effectiveness. Heat transfer augmentation techniques are classified into active and passive methods. Active methods require the direct external power, whereas passive methods do not require any direct external power. There are various techniques to reduce the thermal boundary layer thickness by improving good mixing of the fluids near walls and the center of the tube. Swirl flow generating devices provide chaotic mixing of the fluid and also good passive method of heat transfer augmentation.

Many researchers conducted experiments and numerical simulations by inserting a wide range of twisted tapes, twisted coils and conical-rings into the inner tube of the concentric tube heat exchangers and proved that the thermodynamic efficiency of the system is increased. Heat transfer applications like waste heat recovery methods; refrigeration and air conditioning systems are using this type of swirl generators to enhance the heat recovery.

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Nomenclature

C_P	specific heat, J/kg K
d	tube diameter, m
d_t	twisted tape diameter, m
e	enhancement
f	Darcy friction factor
h	heat transfer coefficient, W/m^2 K
H	total enthalpy, J
k	turbulent kinetic energy, m^2/s^2, thermal conductivity, W/m K
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number
P_t	twisted tape pitch, m
p	pressure, kg/m s^2
Pr	Prandtl number
Q	heat transfer rate, W
q	heat flux, W/m^2
Re	Reynolds number
T	temperature, K, constant time interval, s
t	time, s
U	quantity of parameters (e.g. velocity)
v,u	fluid velocity, m/s
x_i, x_j	cartesian co-ordinates, m

Greek symbols

$\in$	effectiveness
ε	dissipation, m^2/s^3
ρ	density, kg/m^3
μ_b	viscosity, kg/m s
μ_t	eddy viscosity, kg/m s
δ	Kronecker delta
ϑ	viscous stress tensor
τ	Reynolds stress tensor

Subscripts

c	cold fluid
h	hot fluid
l	laminar
t	turbulent

Superscripts

$(\bar{\ })$	Reynolds average, average
$(\tilde{\ })$	Favre average
$(\ )$	Reynolds fluctuation
$(\ )$	Favre fluctuation

Abbreviations

ACT	annularly corrugated tube
CW	corrugation width
HE	heat exchanger
ID	inner diameter
OD	outer diameter
PT	plain tube
TT	twisted tape

Some of the works using different types of swirl generators listed in the literature have been discussed. Al-Fahed et al. [1] conducted the experiments using oil as the working fluid for plain, micro fin and twisted-tape insert tubes and concluded that the heat transfer is being increased with the increase in the twist ratio. Saha et al. [2] investigated the effect of regularly spaced twisted tape elements, experimentally in laminar and turbulent flow regime and reported that the heat transfer increases by 20–40%.

Ray and Date [3] conducted numerical analysis inserting a twisted tape in the square duct and developed correlations for friction factor and Nusselt number and reported that there is a fair agreement between the simulation and the experimental results. Garcia et al. [4] conducted an experimental study on heat transfer in a plain tube with wire coil inserts in laminar-transition-turbulent regimes and stated that the heat transfer rate can be increased by up to 200% keeping pumping power constant.

Eiamsa-ard et al. [5] conducted experiments and reported that Nusselt number is improved by 160% using full length twisted tape and 179% by inserting helical tape with and without rods [6] inside the tube when compared with the plain tube. Naphon and Sriromruln [7] conducted experiments by inserting the coiled wire in the plain tube and found that there is a significant effect of swirl in enhancing the rate of heat transfer.

Chang et al. [8] investigated heat transfer in tube with broken twisted tape inserts experimentally and reported that the thermal performance is improved by up to 0.9–1.8 times of those tubes fitted with plain twisted tape. Heat transfer behavior with conical ring and twisted tape insertions was investigated experimentally by Promvonge and Eiamsa-ard [9] and reported that 367% enhancement in the heat transfer over the plain tube.

Promvonge [10] in another report, mentioned that enhancement in the heat transfer is about 1.2–1.3 times when square wire coil is inserted in a circular tube. Promvonge [11] conducted experiments to investigate air flow friction and heat transfer characteristics in a round tube fitted with both coiled wire and twisted tape and obtained 200–350% enhancement in the heat transfer.

Bharadwaj et al. [12] conducted experiments on spirally grooved tube with twisted tape and reported 140% of heat transfer enhancement over the plain tube. Rahimi et al. [13] also conducted numerical simulations with various twisted tapes and compared with the classic twisted tape and observed around 31% of enhancement in the heat transfer coefficient. Eiamsa-ard et al. [14] performed numerical simulations of swirling flow in circular tube by means of twisted tapes and reported that the mean heat transfer rates are about 73.6% higher than that of the plain tube.

Instead of changing the type of swirl generating device, Thianpong et al. [15] changed the tube type and conducted experiments on a dimpled tube with classic twisted tape and found the enhancement up to 1.66 to 3.03 times that of the plain tube. Similarly, inserting the twisted tapes in the corrugated tube is expected to promote the generated swirl than that of plain tube and also can improve the rate of heat transfer. All the above studies along with the present study are summarized and presented in the Table 1.

SolidWorks flow simulation software has been used to conduct the numerical study on the effect of swirl generated by twisted tapes of various configurations in the corrugated tube heat exchangers. This program is first verified with the renowned correlations for heat transfer coefficient in highly turbulent flow regime and a fair agreement of about ±10% between the simulation results and correlation prediction was observed. The simulation is then applied to diesel engine exhaust gas to liquid heat exchanger. Based on the literature search, this is the first study of this type of gas to liquid heat exchanger.

2. Diesel exhaust heat recovery system

2.1. Current system

The idea has been tested by a power plant in Ruby (Alaska) with vertically installed concentric tube heat exchanger with annularly corrugated tube as inner tube for exhaust and outside tube is plain tube with jacket water which is exiting the diesel engine jacket to capture