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Energy Efficiency Improvements through Optimization of Low Grade Industrial Waste Heat Recovery Organic Rankine Cycle by using Genetic Algorithms and Taguchi's Method

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Abstract

Present work focuses on thermodynamic optimization of Organic Rankine Cycle (ORC) used for waste heat recovery from industries. The effect of variation in operating parameters is studied for three different working fluids. Parameters of the ORC are optimized with thermal efficiency, net work output and exergy destruction rate as the objective functions using genetic algorithm in MATLAB. Optimization of ORC performed by genetic algorithms is compared with that done by Taguchi's method for the similar set of performance parameters and the same waste heat source. Both the methods revealed results in accordance with each other. ORC shows the optimized thermal efficiency with R-245fa and optimized net work output for R-134a. It is found that performance parameters have significant effect on the performance of ORC. By genetic algorithm the optimum performance can be predicted with good accuracy.

Keywords: *Organic Rankine Cycle, Energy Efficiency, waste heat, Genetic algorithms*

1. Introduction

Exhaust temperatures of many industrial applications are lower than 350 ºC. Lot of hot streams of air and water and other fluids are discharged directly into the environment. It leads to the loss of precious heat and this also causes thermal pollution. Statistical investigations show that low grade waste heat accounts for more than 50% of the total waste heat generated in the industry [18]. Many methods and technologies are available to recover some portion of this waste heat but among these methods Organic Rankine cycle is most suitable due to its simplicity of operation and easily availability of its components. ORC is flexible safe and requires low maintenance. It produces work by using waste heat streams from industries and hence virtually runs free. It helps converting low grade energy into high grade energy. ORC differs from the traditional Rankine cycle in terms of working fluid, which, in this case is a low temperature boiling refrigerant. ORC is not a new technology; much research has been done on ORC and its working fluids. Yiping Dai et. al. [1] optimized and compared different ORCs for low grade waste heat and found that the cycles with organic fluids performed far better than those with water as a fluid. Various researchers have compared ORCs run with different working fluids. Saleh et. al. [2] screened thirty one fluids for ORCs operating between very low temperatures and pressures. Rayegan and Tao[3] devised a procedure to select the working fluid for a solar ORC. Fluid selection is very critical for the performance of ORC therefore much of the available research work concentrates on fluid selection. Some of researches have tried to optimize the operating parameters of the cycle. Roy et. al. [4] attempted the performance analysis and parametric optimization of a heat recovery system using ORC . Three different fluids were chosen for the study and Carnot efficiencies were compared. Wang et. al. [5] performed cycle optimization of ORC by using mathematical models. Techno-economic feasibility analysis was performed by Sylivain Quoilin et. al. [6]; a market review is proposed in this work, it also includes cost figures for several commercial ORC modules and manufacturers. In many studies the emphasis is laid on optimizing the cycle by proper selection of the working fluid [7-11].

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2. System Description

ORC uses a low boiling fluid as its working medium. It allows heat recovery from very low temperature sources. Recovered heat may be used to generate electricity. Figure 1 presents the schematic of a simple ORC on a temperature entropy diagram. At point 1 the fluid is at saturated vapor state.

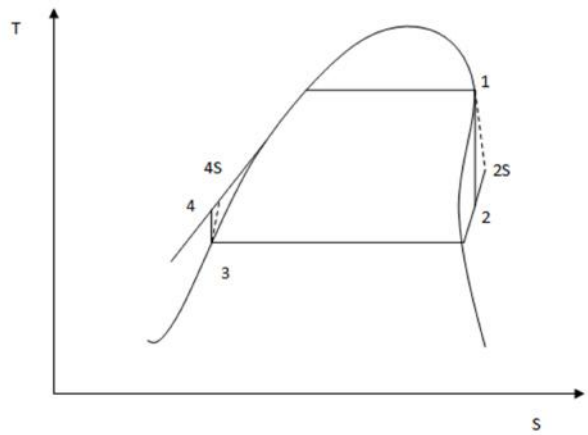


Fig. 1. *T-S* diagram of ORC with dry refrigerant and saturated vapor at turbine inlet

Process 1-2 (Turbine)

It is the adiabatic expansion process in the turbine. For an adiabatic process

$$h_1 - h_2 = \frac{W_{ouput}}{\dot{m}\eta_t} \text{ or} \quad (1)$$

$$W_{output} = \dot{m}(h_1 - h_2).\,\eta_t \text{or} \quad (2)$$

$$W_{output} = \dot{m}.c_p.\Delta T.\,\eta_t \quad (3)$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{1-\frac{1}{\gamma}} \quad (4)$$

$$\text{Or, } T_2 = T_1.\left(\frac{p_2}{p_1}\right)^{1-\frac{1}{\gamma}} \quad (5)$$

$$W_{output} = m.c_p.T_1\left[1 - \left(\frac{p_2}{p_1}\right)^{1-\frac{1}{\gamma}}\right].\eta_t \quad (6)$$

Process 2-3 (Condenser)

Constant pressure phase change takes place in condenser and the working fluid is converted into the saturated liquid.

Condenser heat rate is given by

$$\dot{Q}_c = \dot{m}.(h_3 - h_4) \quad (7)$$

Process 3-4 (Pump)

Pump drives the ORC. Pump work is expressed as

$$\dot{W}_p = \frac{\dot{m}}{\rho.\eta_p}(p_1 - p_2) \quad (8)$$

Process 4-1 (Evaporator)

Process 4-1 is isobaric heat transfer. Working fluid is heated up in the evaporator which is located between pump outlet and turbine inlet. Heat transfer rate is given by

$$\dot{Q}_e = \dot{m}.(h_1 - h_4) \quad (9)$$

Net work obtained by the cycle presented as the difference of turbine work and pump work

$$\dot{W}_{net} = m.c_p.T_1\left[1 - \left(\frac{p_2}{p_1}\right)^{1-\frac{1}{\gamma}}\right].\eta_t - \frac{\dot{m}}{\rho.\eta_p}(p_1 - p_2) \quad (10)$$

Equation 10 serves to be the fitness function for optimizing the net work output. Specific heat at constant pressure have different values for different refrigerants and for different temperatures. Equation 11 shows the thermal efficiency of ORC.

$$\eta_{th} = \frac{\dot{W}_t - \dot{W}_p}{\dot{m}\,(h_1 - h_2)} \quad (11)$$

(h_1-h_2) of a Gas is found by the relation

$$\log_e p = \frac{-dh_{vap}}{R.T} + C, \text{ Or} \quad (12)$$

$$dh_{vap} = -R.T.\log_e p + C \quad (13)$$

Modified equation for the thermal efficiency of ORC is presented in equation 14.

$$\eta_{th} = \frac{\dot{m}\left[c_p.T_1\left[1 - \left(\frac{p_2}{p_1}\right)^{1-\frac{1}{\gamma}}\right].\eta_t - \frac{1}{\rho.\eta_p}(p_1 - p_2)\right]}{\dot{m}\,.c_p[-R.T.\log_e p + C]} \quad (14)$$

It serves as the fitness function for thermal efficiency of the cycle. Average values of γ, C_p, ρ and the constant C are calculated for the desired temperature and pressure range by using REFPROP developed by NIST [17] for all the refrigerants under consideration are presented in Table 1.

Table 1: Mean values of properties of refrigerants

Refrigerant	γ	C_p (kJ/kg-K)	ρ (kg/m^3)	C (kJ/kg)
R-245fa	1.29	1.34	87.78	10823
R-123	1.20	.905	55.67	8456
R-134a	1.18	1.00	34.70	7645

3. Methodology

This research work compares the results obtained in optimization process of ORC through the Taguchi's methods and the Genetic algorithm. Taguchi's method is used to optimize the cycle with a fixed number of parameters at different operating levels. Nature of the number and levels of parameters are discrete in Taguchi's method. Optimum performance is worked out for a desired level of satisfaction by using specially designed orthogonal arrays. On the other hand, a Genetic algorithm works on the principle of optimizing the objective function which is known as the fitness function with some constraints and bounds. Parameters of the fitness function may take the continuous values and due to this more precise optimum point can be located. A brief overview of genetic algorithms and Taguchi's approach is presented in following sections.

3.1 Genetic algorithms (GA)

Genetic algorithms were invented by Professor John Holland in 1975. They and their variants are computational procedures that mimic the natural process of evolution [12]. They are based on the Darwinian survival of the fittest principle. The GA maintains a population of n chromosomes (solutions) with associated fitness values. Parents are selected to mate, on the basis of their fitness, producing offspring through a reproductive plan. Highly fit solutions are given more chances to reproduce, so that offspring inherit quality characteristics from each parent. As parents mate and produce offspring, room is made for the new arrivals since the population is kept at a static size. Individuals in the population die and are replaced by the new solutions creating a new generation. Once all mating opportunities in the old population have been exhausted, new generations of solutions are produced containing better genes than a typical solution in a previous generation. Each successive generation will contain better solutions than previous generations. Eventually, once the population has converged and is not producing offspring noticeably different from those in previous generations, the algorithm itself is said to have converged to a set of solutions to the problem at hand. In this way better and better solutions are ensured and finally they narrow down to the best available solution or optimum solution.GA starts the operation on a population of potential solutions to produce better and better approximations towards optimal solutions. Each individual in the population is called a string or chromosome and each chromosome represents a possible solution. These chromosomes are then subjected to evolution process. Parameters of the problem are termed as genes. In the present work the chromosome is defined as a real number vector.

$$X = (x_1, x_2, x_3, \ldots \ldots \ldots \ldots \ldots \ldots .., x_n) \quad (15)$$

$$x_i \in R$$

$$i = 1,2,3,4, \ldots \ldots \ldots \ldots \ldots, n$$

Where i represents the i^{th} parameter for ORC, n represents the number of optimizing parameters. x represents the operating parameter which is to be decided for the optimum performance of the cycle. Genetic algorithm uses a fitness function to evaluate the adaptability of an individual without external information in the evolution search [14]. The adaptability of fitness function is represented by fitness value, larger the fitness value more is the adaptability. In this work, thermal efficiency and net work output are selected as the fitness function for optimizing the performance of ORC.

GA uses three types of rules at each step to create the next level of generation from the current population. Selection rules decide the individuals, called parents, which contribute to the population of next generation [13]. Parents are chosen on the probability based on its fitness. A higher fitness increases the probability of its selection. The crossover operator produces new chromosomes in GA. It produces individuals having some part of both parent's genetic materials. In a traditional GA, simple crossover operators such as one point of two point crossovers are often used. These crossover operators work by randomly generating one or more crossover points then swapping segments of two parent strings to produce two child strings [25]. To avoid a local solution, the mutation operator is randomly applied with low probability to modify values in the chromosomes. Random mutation is adopted to optimize the parameters of ORC.

A new set of approximations is created at every generation. This happens due to the process of selecting individuals according to their level of fitness. This process leads to the evolution of population of individuals which which are more suited than the individuals from which they are created. Population size, crossover probability, mutation probability and stop generations may be selected as per the requirements of a particular problem.

3.2 Taguchi's Method

Dr. Genichi Taguchi developed a robust statistical approach to improve the quality of manufactured goods. Dr. Taguchi began working for it after World War II. Concepts introduced by him have been accepted as valid extensions to the body of knowledge. Taguchi's method is a powerful tool for the design of high quality systems. It provides simple, efficient and systematic approach to optimize designs for performance quality. The methodology is valuable when the design parameters are qualitative and discrete. It can optimize the performance characteristics through the setting of the design parameters and reduce the sensitivity of the system performance to the sources of variation. In Taguchi's method the engineering optimization of a process/product is carried out in three steps approach that is system design, parameter design and tolerance design. In the process optimization, system design is fixed from the thermal design input [19]. Tolerance design is related to manufacturing, which is not in the scope of thermal process systems. Therefore, Taguchi's approach for parametric design is used for the present work. Taguchi's parameter design optimizes the performance characteristics by the settings of design parameters. In recent years Taguchi's method has been applied to a number of applications in a wide range of industries, but the application of Taguchi's method for energy recovery is limited till date. In present work results obtained by us in our previous work [20] by applying Taguchi's methods to ORC are compared with the results obtained by genetic algorithms.

4. Choice of the Working Fluid

Choice of the refrigerant for ORC applications is very crucial as its properties affect the cycle efficiency and investment cost. Lot of research work has been done particularly for proper selection of working fluids for ORC [21], [22] and [23]. The efficiency of energy conversion of the cycle gets reduced by irreversibilities present at the various stages of cycle. Efficiencies and irreversibilities are very much dependent of fluid properties and working conditions, therefore it is very essential to select the working fluids and working conditions very carefully. Working fluids used for ORC are low boiling refrigerants. They are classified as wet, dry and isentropic fluids [14]. Dry fluids have a positive slope of saturated vapor line in T-S diagram. Dry fluids remain in superheated gas region after expansion in the turbine. In wet fluids the slope of saturated vapor line is negative and cycle state reaches in wet region after expansion in the turbine. Figure 2 represents wet, dry and isentropic fluids on a temperature entropy plot.

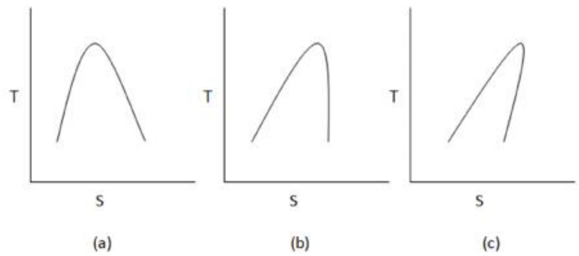


Fig. 2. Different types of working fluids (a) wet, (b) isentropic and (c) dry

Water and ammonia are wet fluids. In case of isentropic fluids the slope of saturated vapor line is infinite and the expansion in turbine takes place along saturated vapor line. Tzu-Chen Hung [24] discussed the properties of available fluids and recommended the use of dry and isentropic fluids for low grade heat recovery ORC. Superheating the fluid as in the case of a normal Rankine cycle run on water is also not suggested for low grade heat sources. Other desirable properties of a refrigerant are (a) low toxicity, (b) Controllable flammability and (c) good material compatibility and fluid stability limits. Working fluids selected for this research work are those found suitable by comparing the desired properties and after going through various researches done in this field. Based on the available literature R-245fa, R-123 and R-134a are selected as the refrigerants for optimizing the performance of the cycle and comparing the results with Taguchi's best.

5. Optimization of ORC

The variation of actual pressures with temperatures was found by REFPROP at the saturation points for the three refrigerants under consideration. R-245fa has higher pressure values for the all temperature ranges within the consideration followed by R-134a and then by R-123. The overall efficiency of a thermodynamic conversion cycle is a consequence of the energy potential of the source-sink combination, of internal inefficiencies which result from the losses in turning machinery and in regenerators and of losses from irreversible heat transfer from a source and to a sink. The latter depends mostly on the levels of matching of the apparent heat capacities of the working fluid, source and sink. Fluids with higher saturation pressures for the same temperatures are likely to be more efficient. Specific heats and vapor densities of R-245fa are larger as compared to other two refrigerants. Optimization was carried out by using genetic algorithm tool box in MATLAB with the following boundary conditions. These boundary conditions largely depend upon the type of available waste heat streams available.

a) For turbine inlet temperature

$$80^oC \le T_1 \le 130^oC$$

b) For condenser temperature

$$20^oC \le T_2 \le 45^oC$$

c) For turbine inlet pressure

$$0.5\ MPa \le P_1 \le 3.5\ MP$$

d) For condenser pressure

$$0.5\ MP \le P_1 \le 3.5\ MP$$

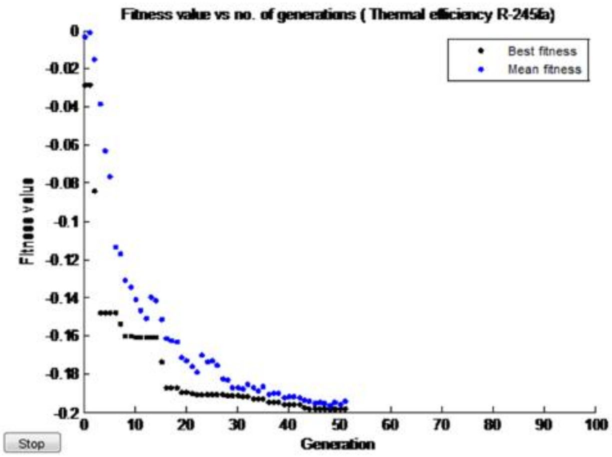
Cycle performance was evaluated with the following assumptions

1. The system has reached a steady state.
2. Pressure drops in the pipes and heat losses to the environment through evaporator, condenser, turbine and pump are neglected.
3. Isentropic efficiencies of pump and turbine are 0.6 and 0.8 respectively and they remain constant throughout the operation.

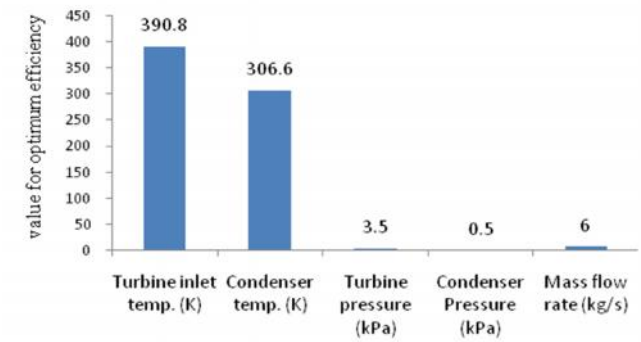
5.1 Thermodynamic optimization

In order to optimize the ORC performance, the concerned operating parameters and their operating ranges are to be set. Saturated vapor is assumed at the inlet and outlet of the turbine and the cycle is assumed to be subcritical. ORC optimization through genetic algorithms is performed in MATLAB using GA toolbox. Equations 10 and 14 served as the fitness functions for net work output and thermal efficiency of the cycle respectively. Thermodynamic properties of refrigerants and their variations with temperatures and pressures are calculated by using REFPROP. In a subcritical ORC the operating parameters to be optimized are turbine inlet temperature and pressures, condenser inlet temperature and pressure, mass flow rate of the refrigerant and the best working fluid. GA starts by seeking a particular set of variable values and iterating towards the optimum through various levels which are known as generations.

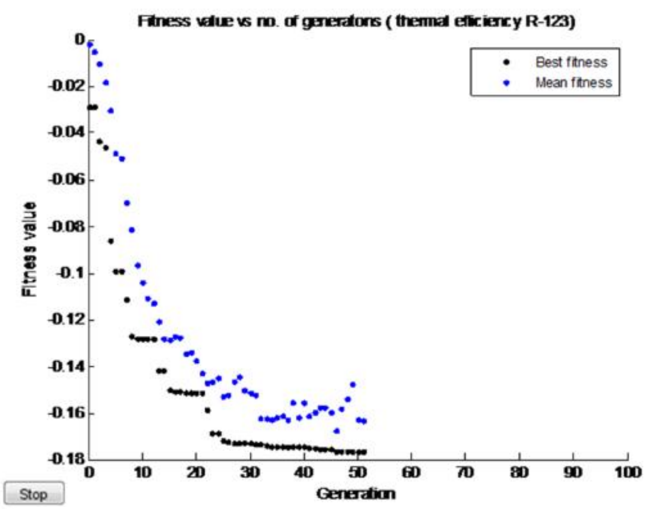
Figure 3(a) shows the variation of fitness values verses the number of generations for optimizing the thermal efficiency using R-245fa as the working fluid. Converging down of the best fitness value as the number of generations increases is visible. Near about 50^{th} generation values are converged down to 20.13 %. Values of operating parameters at this point are indicated in figure 3(b). They corresponds to the turbine inlet temperature of 390.8 Kelvin, condensor temperature of 306.6, turbine inlet pressure of 3.5 kPa, condenser pressure of 0.5 kPa and mass flow rate of 6 kg/s. Figures 3(c) and 3(d) show the fitness value vs number of generations and values of parametes respectively for an optimum thermal efficiency using R-123 as a working fluid in ORC. Remaining conditions are kept constant for the evaluation. Optimum thermal efficiency obtained for this fluid is 19.29 % , which is smaller as compared to R-245fa. Values of operating parameters for the optimum efficiency as presented in figure 3(d) are as follows; Turbine inlet temperature of 378.2 K, Condenser temperature of 317.9 K, turbine inlet Pressure of 3.4 kPa, condenser inlet pressure of 0.5 kPa and mass flow rate of 8.9 kg/s. Other parameters than the type of working fluid are almost similar in both the cases. Charts shown in figures 3(e) and 3(f) are the similar graphs for optimum thermal efficiency of ORC with refrigerant R-134a. The maximum efficiency obtained with this working fluid is 21.53 %. Figure 4(a) and 4(b) are same plots for net workoutput using refrigerant R-245a in the ORC. Values of the optimized parameters for a maximum work output are presented in figure 4(a). Similar plots for the refrigerants R-123 and R-134a are shown in figures 4(c), 4(d), 4(e) and 4(f) respectively. The trend shows that higher turbine temperatures and lower condenser temperatures are resulting in larger values of work output.



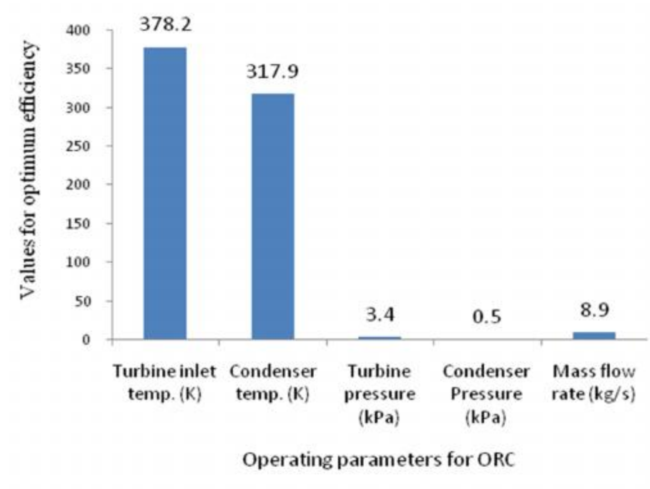
a. Fitness value vs number of generations for thermal efficiency using R-245fa



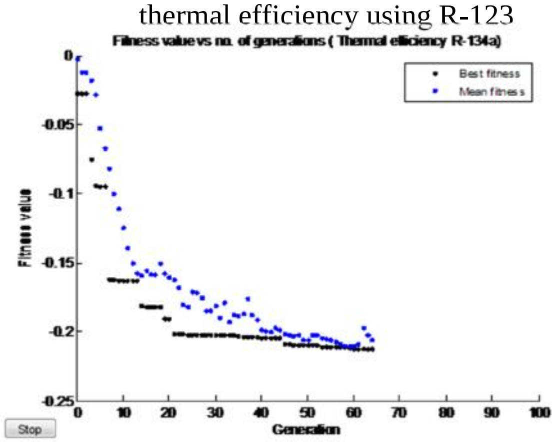
b. Chart depicting the values of operating parameters for maximum thermal efficiency for R-245fa



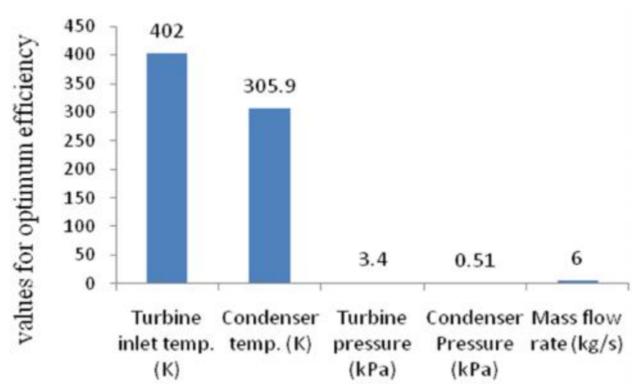
c. Fitness value vs number of generations for thermal efficiency using R-123



d. Chart depicting the values of operating parameters for maximum thermal efficiency output for R-123



e. Fitness value vs number of generations for thermal efficiency using



f. Chart depicting the values of operating parameters for maximum thermal efficiency for R-134a

Fig. 3. Diagrams showing results of genetic algorithm

6. Results and Discussions

An ORC consists of a turbine, an evaporator, a condenser and a fluid pump. The schematic of a simple ORC on temperature-entropy plot is shown in figure 1. Present research work focuses on maximum recovery of waste heat by optimizing the heat recovery ORC to generate electricity from waste heat. Section 2 explained the thermodynamic formulation of ORC in a viewpoint of application of genetic algorithm. Fitness functions were derived for thermal efficiency and net work output, which were further used as the performance parameters for ORC. Results obtained were compared with those obtained in the optimization of the cycle with Taguchi's methods. Results obtained are plotted in figure 3 and 4.

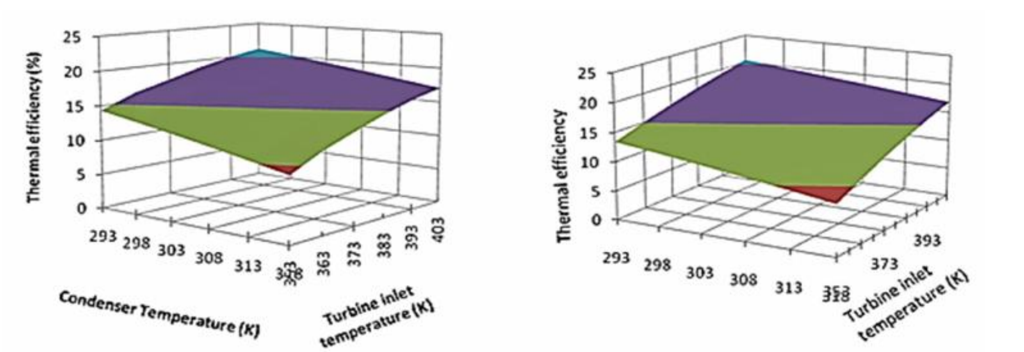
Figures 5(a), 5(b) and 5(c) show that an increase in turbine inlet temperature increases the thermal efficiency. Increase in the condenser temperature results in decrease of the thermal efficiency in all the three refrigerants. Results plotted here indicate the pressure and temperature ranges which are applicable to the cycle under considerations. When the results are plotted for beyond the above temperature ranges it is found that an increasing working fluid mass flow rate improves the thermal efficiency and net power generation initially then it drops. However, the increase and drops are marginal and in the present range the variations seem to be nearly linear.

A higher turbine inlet temperature results in higher thermal efficiency of the system. However, the turbine's inlet pressure cannot be increased arbitrarily as it needs a larger system with increased capital investment and more operational costs. Therefore, is always advised to run the system on turbine's designed pressures. Of the three refrigerants R-134a shows the maximum efficiency of 21.53 % followed by R-245fa and R-123 which show the efficiencies of 20.13 % and 19.29 % respectively.

Variations in the values of optimized thermal efficiencies obtained for the three different working fluids is not much. This can be attributed to a narrow operating range of the cycle controlling parameters. Since the ORC under consideration is a low temperature cycle with the low temperatures. Some other similar works show greater variations in thermal efficiencies. Zhang Shenjun et. al. [26] compared the thermal efficiencies of ORC run with 16 different working fluids.

Difference between the maximum and minimum efficiency was found to be 4% for a low temperature waste heat stream. Figures 6(a) and 6(b) present the variations in net work output of ORC with change in condenser temperature and turbine inlet temperature for three working fluids.

Figure 6(b) presents the variation of net work output of ORC run with working fluid R-123 with condenser temperature and turbine inlet temperature. Net work output decreases with and increase in condenser temperature, However it shows an increasing tendancy with an increase in turbine inlet temperature. Trend of variation for the range under consideration is linear for both the operatinng parameters. A similar type of trends are obtained when work output of ORC run with R-245fa and R-134a are plotted against the same parameters. The maximum work out is obtained for the refrigerant R-245fa. The values obtained for r-245fa is almost double of that obtained with the other two working fluids.



a. variation of thermal efficiency with condenser temprature and turbine inlet temperature for R-245fa

b. Chart depicting variation of thermal efficiency with condenser temprature and turbine inlet temperature for R-123a

c. Chart depicting variation of thermal efficiency with condenser temprature and turbine inlet temperature for R-134a

Fig. 5. Thermal efficiency verses condenser temperature and turbine inlet temperature

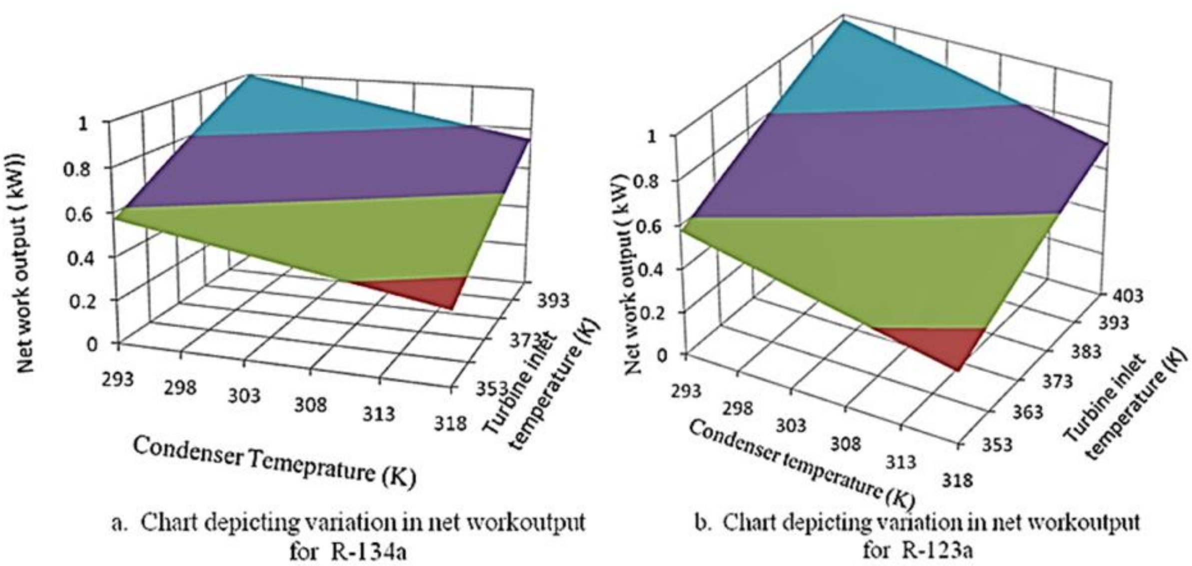


Fig.6. Net work out put verses condenser temperature and turbine inlet temperature

Table 2. Comparison of maximum work output by G.A and Taguchi's approach

	Optimized work output (kW) by using:	
Refrigerant	**Genetic algorithm**	**Taguchi's Method**
R-245fa	2.05	2.14
R-123	.999	0.878
R-134a	.980	0.856

Table 3. Comparison of maximum efficiency by G.A and Taguchi's method

Refrigerant	**Optimized Efficiency (%) by using:**	
	Genetic algorithm	Taguchi's Method
R-245fa	18.9	20.13
R-123	21.53	21.2
R-134a	19.29	17.6

Table 2 presents the results of optimized net work done obtained by genetic algorithms along with the values of parameters for all the three refrigerants.

Figure 7 presents a comparison chart between the results obtained from genetic algorithms and Taguchi's method for optimized net work obtained, the values obtained are plotted separately for each refrigerant. ORC run with R-245 produced maximum work output.

Table 3 presents a comparison of the maximum efficiencies obtained by Taguchi's method and by genetic algorithms.

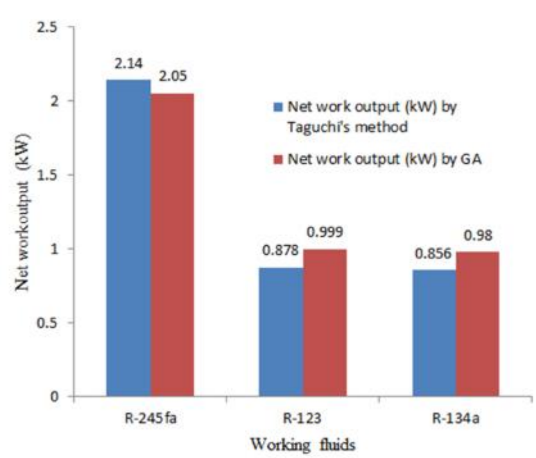


Fig. 7. Comparison of optimum Net workoutput of ORC estimated by Taguchi's method and genetic algorithm

Figure 8 shows a comparison of the results obtained in optimizing the thermal efficiency of ORC by GA and Taguchi's method. Results are plotted separately for all three refrigerants. The maximum thermal efficiency is obtained for R-123 by both the methods. Results obtained by both of the methods are in accordance with each other.

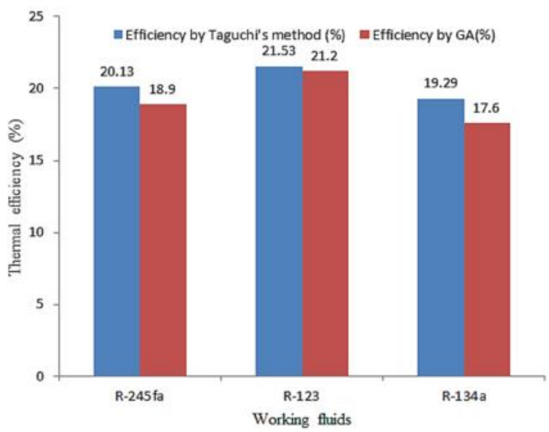


Fig. 8. Comparison of optimum thermal efficiencies of ORC estimated by Taguchi's method and genetic algorithms

7. Conclusion

This paper is an approach towards optimizing ORC run with low grade industrial waste heat. Thermal efficiency and net work output are taken as performance parameters to be optimized. Refrigerants sorted order from higher efficiency to lower is R-245fa, R-134a and R-123, which has been found similar in trend as calculated by sylvain quoilin et. al. [27]. Refrigerants used are either dry or isentropic which avoid the wet steam during expansion in turbine. Trends obtained for net power output and thermal efficiency are similar to those obtained by Jian Sun et. al. [28]. It shows, the net work output increases as the mass flow rate of refrigerant increases. An optimum combination of operating parameters is sought after by the application of genetic algorithms and Taguchi's robust design methods. Results obtained from the two methods are analyzed and compared. Following conclusions are derived from the results obtained:

- Higher turbine inlet temperature results in more work output and thermal efficiency.
- Both the optimization techniques are equally applicable for optimizing the cycle as the results obtained by both the techniques are in accordance with each other, therefore the cycle can be optimized by using any of the above techniques.
- Major limitation of Taguchi's method is the discrete nature of operating parameters whereas in the fitness function of genetic algorithms the variables can have the continuous nature.
- Due to the continuous variables a more precise optimization is obtained through genetic algorithm as compared to the Taguchi's approach.
- Efficiency of the system increases as the heat source temperature increases it requires more mass flow rate of working fluid to extract heat.
- Mass flow rate of the working fluid affects the efficiency and net work output.

Nomenclature

$\dot{m}$	Mass flow rate, kg/s
W	Work, kJ/kg
H	Enthalpy, kJ
p	Pressure, MPa
W_p	Pump power, W
W_t	Turbine power, W
h	specific enthalpy (kJ/kg)
$\dot{I}$	irreversibility rate (kW)
q	specific heat (kJ/kg)
$\dot{Q}$	heat rate (kW)
S	Entropy (kJ/K)
T	Temperature (K)
T_H	temperature of the high-temperature reservoir (K)
T_L	temperature of the low-temperature reservoir (K)
η	efficiency (%)
ρ	density (kg/m^3)
c_p	specific heat at constant pressure (J/kg-K)
R	Gas Constant (J/mol-K)

Subscripts:

bp	boiling point
c	condenser
e	evaporator
t	turbine
p	pump
o	ambient
WH	Waste Heat
P	Pump
K	Condenser

Abbreviations:

DOE	Design of Experiment
ORC	Organic Rankine Cycle
OA	Orthogonal Array
ANOVA	Analysis of Variance
MTOE	Metric ton of oil equivalent

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