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RESEARCH ARTICLE

Engineering

An effective and simplified method to select the working fluid for waste heat recovery based Organic Rankine Cycle

Método Eficaz y Simplificado Para Seleccionar el Fluido de Trabajo Para la Recuperación de Calor Residual Basado en el Ciclo de Rankine Orgánico

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Abstract. Organic Rankine Cycle (ORC) is an attractive option to utilize the low-grade waste heat for power generation. The selection of working fluid for ORC is a challenging task because of environmental constraints as most of the organic fluids has the capacity to damage the environment. In this research, a method for the selection of an optimum working fluid for the operation low grade waste heat is determined. The selection of the optimum working fluids depends upon the thermal efficiency, Global Warming Potential (GWP), Ozone Depletion Potential (ODP) and Atmospheric Lifetime of the fluid. Twelve different organic fluids including R134a, butene, R22, R152a, R245fa, R290, R161a, isobutene, isobutane, dimethyl ether, R600 and R124 are selected for the study. The ORC is analyzed by using EES at 2 MPa, 2.5 MPa and 3 MPa. The thermal efficiency of ORC is determined and is found that high operating pressure is favorable for the operation of ORC. At 2.5 MPa, the top three working fluids are R-245fa, R-600 and Iso-butene with an efficiency of 12.7%, 12% and 11.3% respectively. On the basis of thermal efficiency, R-245fa is the best but it has the highest GWP and atmospheric life of 1050 and 7.7 years. R-600 has GWP and atmospheric life of just 20 and 0.018 years. On the basis of environmental constraints, R-600 is found to be more beneficial than R-245fa. It is concluded that R-600 is the optimum working fluid for the operation of low-grade waste heat ORC.

Keywords: Organic Rankine Cycle, Waste Heat, Working Fluid, Optimization, Environmental Constraints.

Resumen

El ciclo orgánico de Rankine (ORC-por su siglas en inglés Organic Rankine Cycle) es una opción atractiva para utilizar el calor residual de baja calidad para la generación de energía. La selección del fluido de trabajo para ORC es una tarea desafiante debido a las limitaciones ambientales, ya que la mayoría de los fluidos orgánicos tienen la capacidad de dañar el medio ambiente. En esta investigación se determina un método para la selección de un fluido de trabajo óptimo para la operación de calor residual de bajo grado. La selección de los fluidos de trabajo óptimos depende de la eficiencia térmica, el potencial de calentamiento global (GWP-Global Warming Potential), el potencial de agotamiento del ozono (ODP-Ozone Depletion Potential) y la vida útil atmosférica del fluido. Se seleccionaron para el estudio doce fluidos orgánicos diferentes, incluidos R134a, buteno, R22, R152a, R245fa, R290, R161a, isobuteno, isobutano, dimetil éter, R600 y R124. El ORC se analiza utilizando EES a 2 MPa, 2,5 MPa y 3 MPa. Se determina la eficiencia térmica de ORC y se encuentra que la alta presión de operación es favorable para la operación de ORC. Con 2,5 MPa, los tres principales fluidos de trabajo son R-245fa, R-600 e isobuteno con una eficiencia del 12,7 %, 12 % y 11,3 % respectivamente. Sobre la base de la eficiencia térmica, el R-245fa es el mejor, pero tiene el GWP más alto y una vida atmosférica de 1050 y 7,7 años. El R-600 tiene un GWP y una vida atmosférica de solo 20 y 0,018 años. Sobre la base de las limitaciones ambientales, se encuentra que el R-600 es más beneficioso que el R-245fa. Se concluye que el R-600 es el fluido de trabajo óptimo para la operación de ORC de calor residual de bajo grado.

Keywords: Ciclo orgánico de Rankine, calor residual, fluido de trabajo, optimización, restricciones ambientales.

Nomenclature

- Q: Available Heat rate
- $\dot{m}_w$: Mass flow rate of Exhaust gases.
- C: Specific heat capacity of exhaust gases.
- ΔT: Temperature difference of exhaust gases.
- Q_{in}: Rate of heat entered in the evaporator.
- $\dot{m}$: Mass flow rate of working fluid.
- h: Enthalpy of working fluid.
- W_T: Turbine work output.
- Q_{out}: Heat rejected from condenser.
- W_P: Pump work input.
- η_T: Thermal Efficiency of the cycle.

1 | INTRODUCTION

Due to continuous depletion and rising prices of fossil fuels, scientific community is looking for an alternate of fossil fuel to fulfil their daily energy demands. In our country Pakistan, around 63% of electricity is produced by fossil fuels [1] while oil import is around 135,201 per day [2, 3]. So, it's the right time to look for an alternate of fossil fuel-based power generation system. The alternates of the fossil fuel include solar, wind, biomass, hydro as well as waste heat recovery. In conventional power plants, huge amount of energy is being dissipated as waste heat [4]. This waste heat can be used to run the chillers for cold water production, air- conditioning, heat recovery steam generators and to run Organic Rankine cycle (ORC) for electricity generation [5, 6, 7, 8]. Among all, ORC is the best method to utilize the waste heat for electricity generation and to reduce the dependence on the fossil fuels. ORC was first proposed by Howard [9] who examined the use of ether as working fluid in a power plant.

The schematic of ORC is shown in Fig. 1-(a). It is analogous to conventional Rankine cycle but with organic working fluid. There are four basic equipments of ORC viz: Pump, Evaporator, Turbine and condenser. Working fluid enters into the pump where energy is being added into the fluid which ultimately increases the pressure of the fluid. This process is also termed as isentropic compression (process 1-2) as shown in Fig. 1-(b), which then sent to the evaporator. In evaporator, the fluid is being heated at constant pressure as evident from the T-s diagram (process 2-3) and ultimately fluid changes its phase from liquid to vapor. After being transformed into the vapor, the fluid is sent to the turbine where expansion is done as shown in process 3-4 of T-s diagram (Fig. 1-b) and thus producing the power and then condenses to the initial state by rejecting heat to the ambient conditions as shown in process 4-1 in T-s diagram.

Different researchers have analyzed the ORC with different working fluid [10, 11]. Drescher [12] investigated a system to compute the efficiency of ORC along with adequate precision depend on the DIPPR database and Peng-Robinson-EOS. This strategy is applied to select the appropriate fluid for biomass-based ORC. Tchanche et al. [13] selected the best fluid for low temperature ORC run through solar energy. They have investigated 20 different working fluids and found that R134a is the most suitable fluid. R152a, R600a, and R290 has performed in a better way but has environmental issues. Douvartzides and Karmalis [14] have found that by selecting the optimum working fluid, the plant efficiency can be increased up to 6% and fuel requirement can be decreased by 13%. Rayegan and Tao [15] has presented the procedure for selecting the working fluid for solar ORC by comparing the capabilities of working fluids under alike working conditions. Yamamoto et al. [16] has investigated the application and feasibility of the closed cycle ORC with working fluids like HCFC-123 and water hypothetically and practically. From the mathematical calculations, it was evident that the ideal working conditions for water as a working fluid is the greater temperature at the inlet of the turbine which gives the higher turbine work. Alternately, the best working conditions for HCFC-123 occurs when the inlet temperature of the turbine is as low as possible but should be greater than the boiling temperature of the working fluid. In the case of liquid, having the small value of latent heat of fusion is utilized, the best working condition is obtained when fluid is entered in the turbine in the form of saturated vapor. Also, it is exhibited that the cycle efficiency is improved greatly when using HCFC-123. Schuster [17] has carried out the exergy analysis for different working mediums and analyzed these mediums in the conditions of super-critical and sub-critical vapor parameters. On account of supercritical boundaries, an 8% of improvement is noticed in the system efficiency resulted in better exegetical efficiency. Hettiarachchi, et al. [18] tested four suitable working fluids for geothermal binary power cycles for low-temperature to observe their suitability using heat transfer area to net power output ratio. The total plant cost can be measured using this ratio. It can be seen from the results that by properly selecting the working fluid, the efficiency can be increased by more than twice in some cases. Wang et al. [19] has performed the parametric study of ORC with R134a as working fluid and found that the system is technical as well as economically feasible. Kang [20] has experimentally evaluated the performance of ORC using R245fa as working fluid and found that the cycle is 5.22% efficient with 78.7% turbine efficiency. Freeman et al. [21] has examined the potential of power generation using ORC run through combined heat and power scheme and reported that system is able to produce 1070 kW h yr-1 of electricity with 6.3% efficiency. There are some other research groups [11], [22, 23, 24, 25] who have analyzed the ORC as a waste heat recovery system and reported the ORC is best suited for the utilization of low-grade waste heat. Lim et al. [26] have optimized the working fluids for double stage ORC by studying the six different working fluids including R123, R141b and R601in cycle 1 while R245a, R236a and R1233zd in cycle 2. The optimization was done by considering the economic aspects. It was found that the combination R601-R245fa is the best suited with a payback of just 4.21 years.

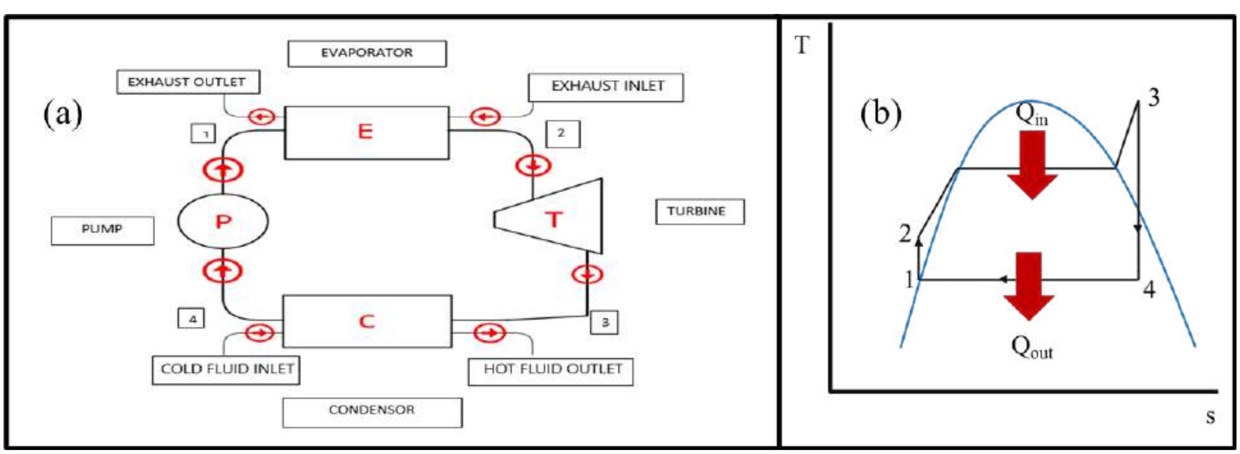

FIG. 1 (a) Schematic of the Organic Rankine Cycle, (b) T-s Diagram of ORC.

From the above discussions, one can conclude that ORC is the best option to capture the low-grade heat and utilize waste heat. Up to the best of authors' knowledge, different researchers have optimized the working fluid for ORC run through solar energy, biomass and geothermal applications but no one have optimized the working fluid for low grade waste heat recovery by considering the thermal efficiency and the environmental impacts. Here, ORC for the waste heat recovery of local automotive industry is analyzed by considering the different working fluids and by variation of working pressure. The analysis is conducted using Energy Equation Solver (EES) software. The working fluids selected for the study are R134a, butene, R22, R152a, R245fa, R290, R161a, isobutene, isobutane, dimethyl ether, R600 and R124. The working fluid is optimized on the basis of cycle efficiency and by considering the environmental effects.

2 | METHODOLOGY

The ORC is designed as the waste heat recovery system for the local automotive industry. The automotive industry is located in Karachi. The available heat rate from waste heat in the industry can be estimated by

$$Q = \dot{m}_w C \Delta T. \tag{1}$$

This waste heat can be utilized to convert the liquid organic fluid into the vapor form in the evaporator section of ORC. The amount of heat gained by the fluid can be determined by

$$Q_{in} = \dot{m}v(h_2 - h_1). \tag{2}$$

In the turbine, the expansion process takes place and the energy absorbed from exhaust gases is converted into mechanical work which is then converted into electrical energy by means of generators. The power produced by the turbine is shown by the following equation

$$W_T = \dot{m}(h_2 - h_1). \tag{3}$$

The fluid after expanding in turbine leaves the turbine in the form of liquid, gas or mixture of both depending on the process conditions and properties of working fluid now enters the condenser and get condensed into liquid before going into the pump.

The rejected amount of heat from the condenser can be determine by following formula

$$Q_{out} = \dot{m}(h_3 - h_4). \tag{4}$$

Fluid enters the pump in the form of saturated liquid and gets pressurized to the sub cooled state and that pressurized fluid from the pump then enters the evaporator pressure at constant entropy. The amount of power utilized by the pump is determined by the following equation

$$W_P = \dot{m}(h_1 - h_4). \tag{5}$$

The thermal efficiency is the ratio of the network output of the cycle to the heat added in the evaporator

$$\eta_{Thermal} = \frac{W_{Trubine} - W_{pump}}{Q_{in}}. \tag{6}$$

3 | BOUNDARY CONDITIONS

The boundary conditions for the software are taken as follows

- Mass flow rate is independent throughout the cycle. $\dot{m}$ = 1 kg/s
- The exhaust gas has a temperature of 200°C.
- The Evaporator pressure of P_1 = 2 MPa, 2.5 MPa and 3 MPa is selected
- The condenser temperature is assumed to be T_4 = 50°C.
- Superheating of 30°C is assumed from a range of 10°C to 40°C. [27, 28]
- Turbine inlet temperature $T_2 = T_b + 30C$
- The isentropic efficiency of turbine and pump are 85% and 70% respectively [27]
- The efficiencies of the equipments are presented in table 1 which are also entered as boundary conditions.

TABLE 1 Operating parameters for ORC [27].

Equipment	Isentropic efficiency
Turbine	85%
Pump	70%
Generator	97%

4 | SAFETY CRITERIA AND ENVIRONMENTAL HAZARDS

While selecting the fluid, top preference is given to the working fluid that is the safest with respect to the environment . Despite of being thermodynamically good, many fluids like CFC and HCFC are already banned because of having the higher potential of depleting ozone and global warming. The Global Warming Potential (GWP) is simply a measure of warming caused by a substance, for which CO_2 (GWP=1) and H_2O (GWP=0) are taken as upper and lower references [29]. The Ozone Depletion Potential (ODP) is simply the ability to destroy ozone's stratospheric layer. The toxicity, ODP, and GWP are also considered for the selection of optimized working fluid.

TABLE 2 Environmental characteristics of the working fluids considered for the study [29, 28].

S.no	Name of working fluid	NBP [K]	Critical temp [K]	Critical Pressure [kPa]	Salty group	Atmospheric life time	ODP	GWP [100 years]	Expansion
1	R-134a	247	374	4059	A1	14.6	0	1300	wet
2	Butene	266.69	419.14	4005	-	-	-	-	dry
3	R-22	232.2	369.1	4990	A1	11.9	0.04	1790	wet
4	R-152a	258.98	386.26	4517	A2	1.5	0	140	wet
5	R-245fa	288.14	427	3651	B1	7.7	0	1050	dry
6	R-290	231	369.7	4247	A3	-	-	-	wet
7	R-161	235.4	375.2	5090	-	0.18	0	12	wet
8	Iso-butene	266	506.96	4010	-	-	-	-	dry
9	Iso-butane	261.3	407.7	3630	A3	0.016	0	20	dry
10	Dimethyl ether	248.2	400.23	5340	A3	0.015	0	-	wet
11	R-600	272.5	425	3800	A3	0.018	0	20	dry
12	R-124	261	395.3	3062	A1	5.9	0.02	619	dry

5 | RESULTS AND DISCUSSIONS

The system is designed for the local automotive industry located in Karachi. The amount of waste heat available is determined by Eq. (1). The available mass flow rate of the exhaust gases was taken unit mass and at a temperature of 200°C.The exhaust gases were cooled down to 90°C. Available heat was found to be

510.7kJ/kg and this amount of heat can be utilized for ORC. This heat is supplied to the evaporator of ORC, where the phase change process occurs. Working fluid enters the evaporator as saturated liquid where exhaust gas loses its energy and the same amount of energy is gained by the working fluid. The working fluid then exits the evaporator as superheated steam with a 30°C of super heat and 3 different pressures in the evaporator are selected for study i.e., 2, 2.5 and 3 MPa.

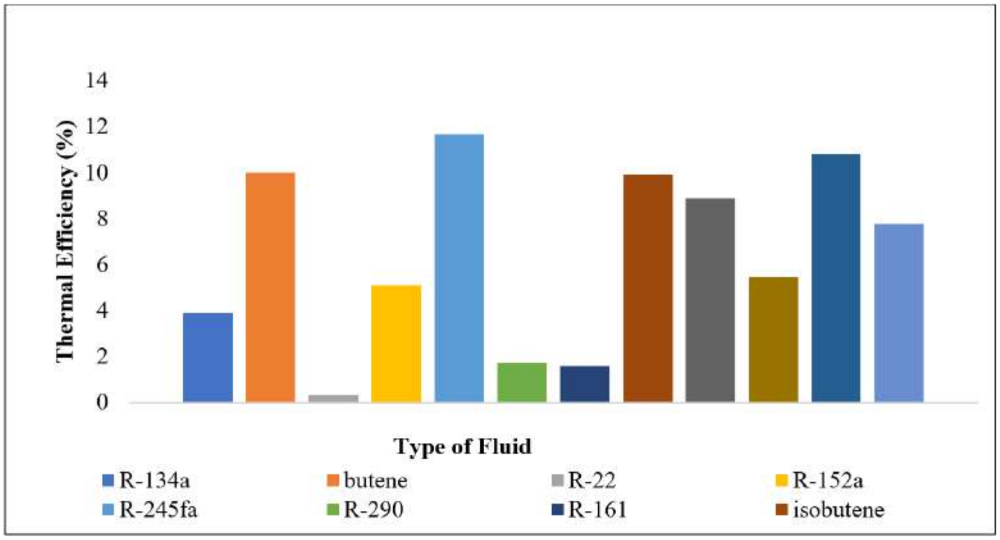

FIG. 2 Thermal efficiency of different working fluids at P=2MPa.

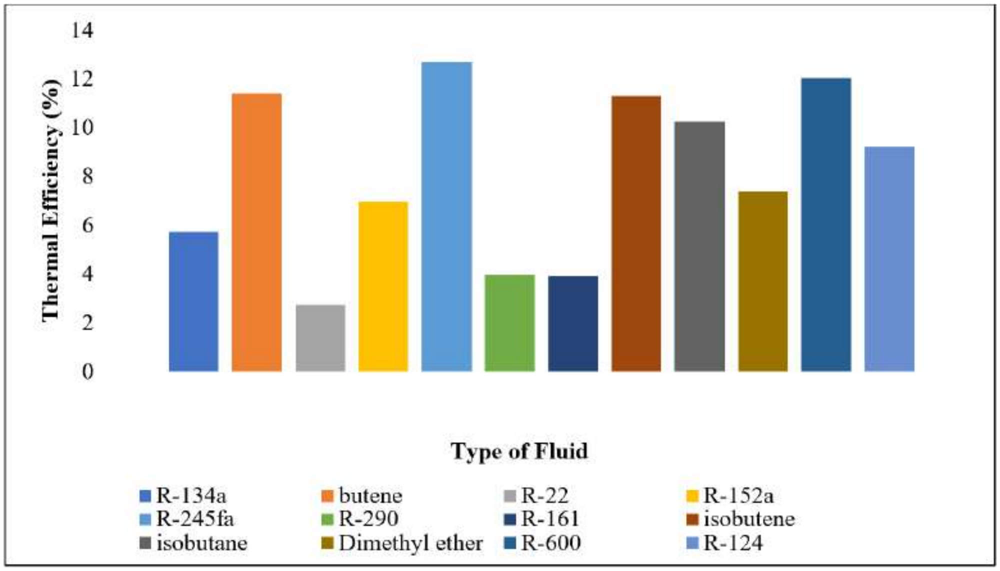

FIG. 3 Thermal efficiency of different working fluids at P=2.5MPa.

The working fluid is expanded in the turbine and transfer its energy to produce mechanical energy and by using generators. This mechanical energy will be transformed into electrical energy. Then the working fluid enters the condenser where it gets sub-cooled at a temperature of 50°C and at condenser pressure below the atmospheric pressure. The working fluid is then condensed to saturated liquid at the pump inlet, the fluid must not contain any moisture and must be in the liquid state. Different working fluids have been selected for prior calculations to find out the most optimum working fluid as per requirement and to get maximum efficiency of ORC. The selection of working fluid depends upon its thermodynamic properties, critical pressure and temperature, and most importantly their environmental aspects i.e., ODP, GWP, and ATM LIFETIME.

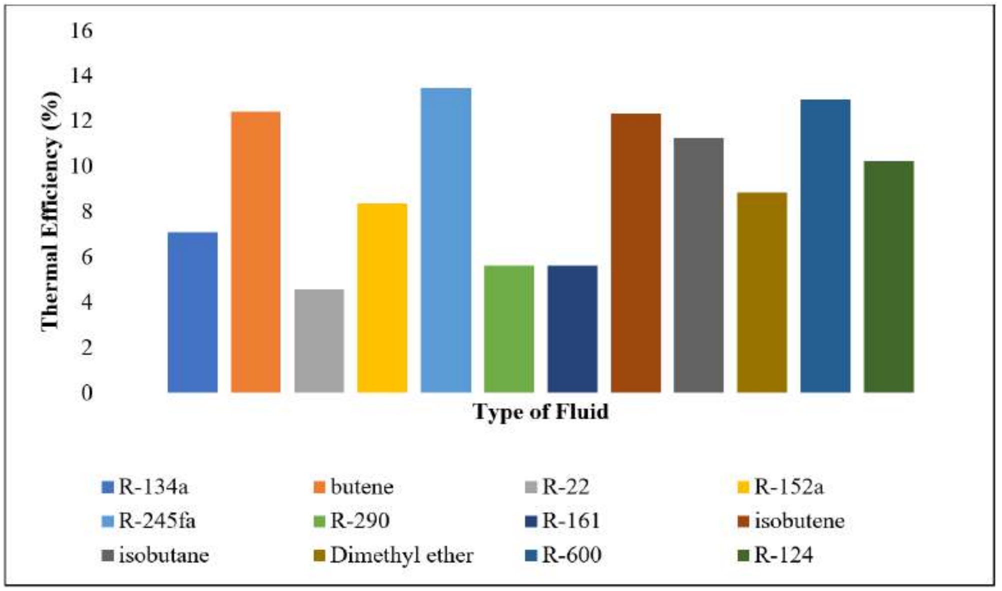

FIG. 4 Thermal efficiency of different working fluids at P=3MPa.

The ORC is analyzed by the Eqs. (1) to (??) to find the thermal efficiency of the different organic working fluids. The efficiency of the ORC by using different working fluids at different pressure is presented from Figs. 2, 3 and 4. Fig. 3, displays the thermal efficiency of the working fluids at 2.5 MPa pressure. From Fig. 3 it is evident that R134a has an efficiency of 5.7%, butene has an efficiency of 11.4%, R22 has an efficiency of 2.7%, R152a has an efficiency of 6.9%, R245fa has an efficiency of 12.7%, R290 has an efficiency of 3.9%, R161 has an efficiency of 3.92%, isobutene has an efficiency of 11.3%, isobutane has an efficiency of 10.27%, dimethyl ether has an efficiency of 7.93%, R600 has an efficiency of 12% and R124 has an efficiency of 9.2%.

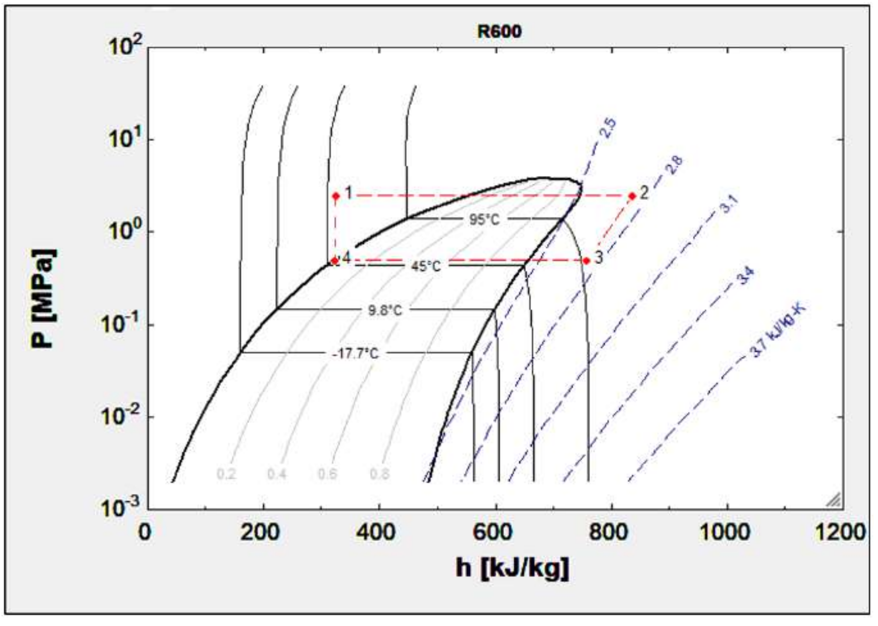

FIG. 5 P-h diagram for R600 at 2.5MPa.

Among all the working fluids the top three working fluids are R245fa, R600 and iso butene with an efficiency of 12.7%, 12% and 11.3% respectively. This means that these three fluids are the best suitable fluid for the working of ORC. But, the selection of optimum fluid does not entirely depend on the thermal efficiency of the working fluids but also depends upon the environmental impacts.

It is also clear from the Figs. 2 to 4 that by increasing the evaporator pressure, the efficiency of the cycle increases. The pressure-enthalpy diagram of ORC with working fluid R-600 is shown in Fig. 5. By increasing the evaporator pressure, the efficiency of the working fluid increases which means that high pressure is favorable for the operation of ORC but high temperature requires more strengthen materials which means more investment. Also, by increasing the evaporator temperature, the boiling point of the working fluid increases. The temperature-entropy diagram is shown in Fig. 7, which clearly indicates that high-temperature heat input is favorable as it overall increases the cycle efficiency but for waste heat recovery systems, the heat input temperature is always low because the majority of the heat is utilized in the main process and the leftover heat is available to run ORC. Thus, high temperature is unable to achieve in low-grade waste heat recovery systems. Therefore, for low-grade waste heat recovery ORC, high pressure is not favorable for the process, therefore a moderate temperature of 2.5 MPa is the most suitable for the operation of ORC.

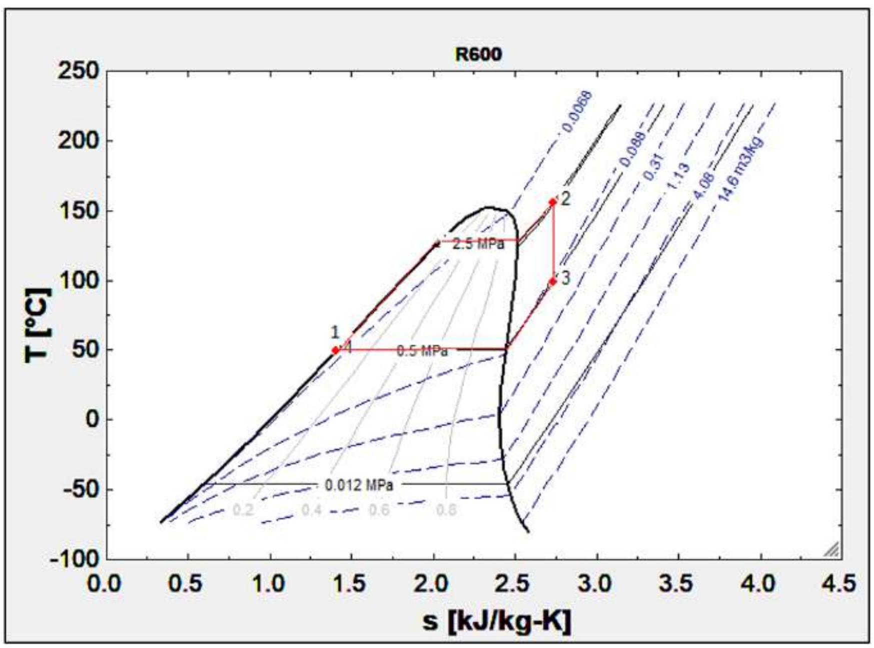

FIG. 6 TS diagram for R600 at 2.5MPa.

The environmental effects of all the working fluids studied are mentioned in table 2. The GWP of R-245fa, R-600 and iso butene are 1050, 20 and 0. The comparison of GWP along with CO_2 is presented in Fig. **??**. From where, it is evident that the GWP of R-245fa 1050 times high as that of CO_2 which indicates that R-245fa is the major threat to the environment because of higher GWP among the other two. The GWP of R-245-fa is high because it is from the group of hydrofluorocarbons (HFCs) and all HFCs are able to trap more heat as compared to CO_2 for a given mass. Although the thermal efficiency of R-245fa is the highest among all the working fluids but due to higher GWP, it is not suitable to use as a working fluid in ORC. The ODP of R-245fa, R-600 and iso butene are zero, it means that these fluids have no threat to the ozone and they will not create any damage to the ozone layer. On the basis of ODP the best fluid is R-245fa. The atmospheric life of R-245fa, R-600 and iso butene are 7.7, 0.018 and 0 years respectively. It means that R-245fa will take around 7.7 years for complete chemical decomposition and to retain the equilibrium condition. R-600 will remain in the atmosphere for 0.018 years. On the basis of the atmospheric life of the cycle, the best fluid is R-600 because of lower atmospheric life. R-245fa is not suitable for the operation despite of being higher thermal efficiency due to higher atmospheric life.

On the basis of thermal efficiency, the best fluid is R-245fa but it is not suitable for the operation of ORC because of higher GWP and atmospheric life. So, to take into account the environmental aspects, the optimum fluid is R-600 as it has the second highest thermal efficiency among the other fluids i.e., 12% at 2.5 MPa and also it has the lower GWP and atmospheric life. It means that R-600 is the ideal candidate for the operation of ORC with maximum efficiency and with a lower environmental hazard. The P-h and T-S diagrams at 2.5 MPa of ORC with R-600 are shown in Figs. 1 and 7. It is clear that both high pressure and high-temperature are favorable for the operation of ORC, as efficiency is increased by increasing the operating temperature and pressure of ORC.

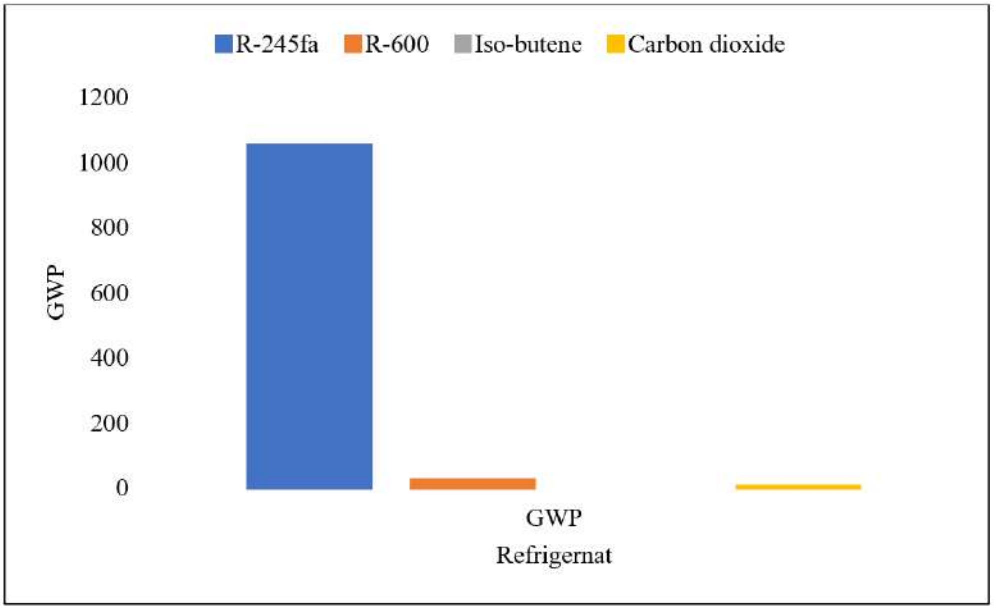

FIG. 7 Comparison of GWP of three highly efficient working fluid with CO_2.

6 | CONCLUSIONS

Organic Rankine Cycle for the utilization of low-grade waste heat is designed and the optimum working fluid is selected. Twelve different working fluids have been selected for the study. The studied working fluids were R134a, butene, R22, R152a, R245fa, R290, R161a, isobutene, isobutane, dimethyl ether, R600 and R124. The optimum working fluids is selected on the basis of higher thermal efficiency, lower GWP, lower ODP and lower atmospheric life. The cycle is analyzed at three different working pressure i.e., 2 MPa, 2.5 MPa and 3 MPa. At 2.5 MPa, R-245fa has the highest thermal efficiency of 12.7% while R-600 has the second highest of 12%. Although, R-245fa has the highest thermal efficiency but it is not favorable for the environment because of higher GWP and atmospheric life of 1050 and 7.7 years respectively. While R-600 has the lower GWP and atmospheric life of 20 and 0.018 years. On the basis of calculations, it is concluded that the optimum working fluid for the operation of low-grade waste heat is R-600 with higher efficiency and with lower environmental constraints. It was also concluded that higher operating pressure and temperature is favorable for the operation of ORC.

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Declaration of Interest

The authors declare that there is no conflict of interest.

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