



## Thermodynamic analysis of modified rankine cycle used for power generation

**R.S. Mishra, Manish Kumar**

*Department of Mechanical Engineering, Delhi Technological University, Bawana Road, Delhi, India*

### Abstract

In this study the modified Organic Rankine Cycle focuses the performance of Internal Heat Exchanger (IHE) in ORC (Organic Rankine Cycle) systems. Although previous studies hold multitudinous opinions, this study gives clear statements of IHE is both subcritical and supercritical ORC systems by setting a new model taking pressure drop in loops and pinch point into consideration. Commonly used working fluids R123 and R245fa are chosen for subcritical and R600 for supercritical cases. The temperature of the heat source applied is 200 °C and the mass flow rate of it is 1kg/s. A modified method of calculating maximum heat exchange in the international heat exchanger (IHE). The results provides that IHE is beneficial to a subcritical case. © 2018 ijrei.com. All rights reserved  
*Keywords:* Modified Rankine Cycle, Thermodynamic Analysis

### 1. Introduction

Energy security, economic development and environment protection are not well balanced today and the energy demand is still closely connected to the economic growth. At the same time, the increasing consumption of fossil fuels has led to more and more environment problems such as global warming, ozone depletion and atmospheric pollution. Fossil fuels still play the dominant role in energy resources worldwide, accounting for 77% of the increasing energy demand 2007-2030 (IEA, 2009). Furthermore, along with the fast Development of industry, energy shortages and blackouts have appeared more and more frequently all over the world. Due to all these reasons, utilizing low-grade waste heat for energy production has attracted more and more attention for its potential in reducing the fossil fuel consumption. The most commonly investigated in low-grade heat source and waste heat utilizations today are Organic Rankine Cycles

(ORCs) and Kalina cycle (binary fluids and fluid mixtures). When utilizing low grade waste heat, the traditional steam Rankine cycle does not give satisfactory performance due to its low thermal efficiency and large volume flows; and thus so called Organic Rankine cycle (ORCs) have been proposed. These cycle use organic substances as working fluid system consist of at least five major comparison with the CO<sub>2</sub> process later, a regenerator is also included in the current calculation. According to waste heat recovery report by U.S. DOE, industrial processes in the United States consumes approximately 35 quadrillion BTU (Quads) of energy per year (BCS Inc., 2008). This amount is about 30% of total energy consumed in the United States. This report categorizes the waste heat based on the temperature of the waste products. The three waste heat groups are: low, medium, high temperature. Table 1 also shows of waste heat and work potential of each waste heat group (BCS Inc., 2008). The waste heat and work potential is based on the reference temperature of

*Table 1: Yearly National Unrecovered Heat*

	Temperature		Waste Heat (trillion BTU per year)		Work Potential (trillion BTU per year) 770F [25°C] Ref [2]
	0F	0C	770F [25°C] Ref [2]	3000F[150°C] Ref [2]	
Low	< 450	<230	903	37	287
Med	450-1200	230-650	466	130	216
High	>1200	>650	108	89	86
Total	-	-	1478	256	589

This data indicates that low temperature heat source results in 60% of total waste heat source. It is estimated that 290 trillion BTU per year or 33% of this low temperature heat can be recaptured into useful works. Low temperature heat source recovery presents the largest opportunity to recover among other discarded heat.

## 2. Organic Rankine Cycle

Organic Rankine Cycle can generate power from natural and waste heat sources such as geothermal sources, biomass, solar radiation and waste heat coming from industrial processes and fuel consumption, solar radiation etc. Therefore, it is considered an important and promising method of renewable energy production process. The organic Rankine cycle uses an organic substance as a working fluid as is implied by the word "organic". In organic Rankine cycle power system, the working fluid selected should maximize the thermal efficiency considering the heat source and long term performance temperature range. The temperature range is from ~100°C to about ~350°C. Rankine cycle gives the highest efficiency when low temperature heat is converted into electricity. The waste heat coming from combustion engines and processes in industries: hot exhaust gases coming from blast furnaces in steel industry and from the kilns in ceramic industry, exhaust gases coming from the engines and turbines, hot liquids that are used to cool kilns and furnaces etc. The organic Rankine cycle uses organic fluid as working fluid instead of water. Organic Rankine Cycle is used for establishment of many commercial plants and test plants. The refrigerants that are used most commonly in ORC include R123, R600, R11, R114 etc. These days the interest is focused on new refrigerants like R1234yf, R1234ze etc. The net output, first and second law efficiency are the indicators of system performance besides the working fluid properties. As far as maximum pressure is concerned, the ORC can be subcritical or supercritical. The cycles can be employed with internal heat exchanger or without IHE. Certain discussions are continuing with some reports stating that exergy efficiency and power output stays unchanged while some stating thermal efficiency rises but output is stationary. It is also stated that induction of IHE greatly reduces expansion ratio, evaporation pressure being below a certain limit. Rankine Cycle gives the best efficiency and power output with an organic fluid as a working fluid instead of water when waste heat at moderate inlet temperature is used as a heat source. This is attributed to the fact that the specific vaporization heat of water is much higher than organic fluids. Thus, the heat source fluid that is to be cooled is followed better by the organic working fluid. In the ORC process more electric power can be generated from a heat source as the exhaust gas is cooled to a lower temperature.

### 2.1 Working Fluids

The following working fluids in this study: R123, R600, HFO-1234yf, HFC-134a, HFC-245fa, iso-pentane. Many researchers investigated these working fluids and are

representative working fluids that are used in ORC, Not only HFC-134a is used but also HFC-245fa and iso-pentane are used in ORC to recover low heat from the industrial plants. Ethanol performs very well at medium temperature levels i.e. 200-300°C hence, it is also recently being used as automotive ORC working fluid. The evaporation temperature of organic substances is relatively lower as compare to steam, this being the main reason and advantage of using them as working fluid in ORC. The low evaporation temperature makes it possible for them to vaporize or superheat by low or medium temperature heat sources. In addition to this, the expander life can be extended by using the organic substances which are categorized as dry or isentropic fluids. Under the saturated or superheated vapour conditions, the vapour that is expanded inside the expander tends to be dry. The major focus today is kept on the subcritical cycle, but some of the research on supercritical cycle employing heat exchanger has also been done. The goal of this study is to find the essential effects of internal heat exchanger on the subcritical as well as supercritical organic Rankine cycle. The performance evaluation parameters consists of net power output, thermal efficiency and also the exergy efficiency. The study analyses the subcritical and supercritical model separately and for locating the pinch point and calculating hot stream outlet temperature, a nested iteration method is proposed. It is found in the conclusion that the system performance is promoted by internal heat exchanger in subcritical case whereas in supercritical cases the internal heat exchanger's effects are dependent on a certain evaporation pressure.

### 2.2 Saturated Cycle Model

It is the most basic cycle that can achieve a compact system design relative to acceptable thermal efficiency when recovering low temperature waste heat.

The T-S diagram of the cycle in the Fig 1.2. The working fluid in the evaporator at a constant pressure after isentropic pumping until it becomes saturated vapor which is then followed by isentropic expansion process.

Depending on the working fluid, the phase condition of working fluid during the expansion process goes two-phase mixture for wet fluids, goes to superheated state for dry fluids and becomes saturated vapour for isentropic fluid. After the expansion process, isobaric condensation takes place in the condenser, which return fluid to saturated liquid state.

### 2.3 Trilateral Cycle Model

It is a simple cycle as compare to conventional binary cycle, its performance is more competitive for low temperature heat sources, especially when a proper two phase expander is employed. Furthermore, it has a lower operational cost for equivalent sized components.

This cycle consists of two features, first being that the working fluid temperature profile tends to match the heat source temperature profile perfectly and the second one is that it operates at reasonable pressure. The schematic diagram is

shown in the Figure 1.3. The pumping pressure which is theoretically same as evaporation pressure lies below the critical pressure of working fluid, and the temperature at expander inlet is maintained at a target saturated temperature. The cycle consists of isentropic state of working fluid followed by isobaric heating of the working fluid to the bubble point. Isentropic expansion of working fluid to a two phase mixture is then induces and finally an isobaric condensation occurs to return the two phase mixture back to a liquid state. The primary difference between natural and conventional cycle is that the working fluid remains a liquid as it leaves the evaporator and the fluid expansion through expander occurs within the two-phase range.

#### 2.4 Superheated Cycle Model

As compared to trilateral and saturated cycle, the superheated cycle allows more heat to enter the ORC system and changes the working fluid state to superheated state. In some cases, the superheated cycle results in higher thermal efficiency than that of saturated cycle.

After the isentropic pumping process, heating process takes place until the working fluid phase changes to superheated state, the temperature being higher than saturated vapour state, the pressure level being kept the same. As the higher expander inlet temperature results in higher power production therefore the temperature is kept higher than the critical temperature at the expander inlet. The working fluid then passes through the expander with isentropic expansion and then condenses to saturated liquid at constant pressure.

#### 2.5 Subcritical Cycle Model

The subcritical cycle have almost operational condition as in superheated cycle, however, the pumping pressure is kept higher than the pressure used for the superheated cycle but slightly lower than the critical pressure.

The T-S diagram is shown in the Figure 1.5 which looks like the superheated cycle. The processes involve isentropic pumping followed by isobaric heating, isentropic expansion and finally isobaric condensation. The expander inlet temperature is kept higher than the critical temperature of working fluid after the expansion process in this cycle.

#### 2.6 Supercritical Cycle Model

In the supercritical Cycle, the expander inlet conditions i.e. pressure and temperature are kept higher than the critical point of working fluid. The main advantage of the cycle is that the hot source temperature can be raised to a higher level that cannot be reached in other cycles.

Serrano et al. [1], did the theoretical investigation and has suggested the feasibility of introducing a waste heat recovery system in two stage turbocharged HDD engine. The WHR is attained by introducing a Rankine cycle, which uses an organic substance or directly water as working fluid depending on energetic performance considerations. They also suggested an

alternative for improving the overall thermal efficiency of Diesel engine consists of recovering the energy lost by means of a waste heat recovery (WHR) system. These solutions are based on adapting one of the turbochargers by removing its turbine and trying to recover the energy by Rankine cycle. Finally, the turbine of the rankine cycle supplies the recovered energy directly to the compressor of this turbocharger.

J. et al. [3] suggested the method for customizing an organic rankine cycle to a complex heat source for efficient energy conversion, demonstrated on a Fischer Tropsch plant. Organic Rankine Cycle provide an alternative to traditional steam rankine cycle for the conversion of low grade heat source into power, where conventional steam power cycle is known to be inefficient. A large processing plant often has multiple low temperatures waste heat source available for conversion to electricity by a low temperature cycle, resulting in composite heat source with a complex temperature-enthalpy profile. Organic fluids are modeled using a pure substance database. The pinch analysis technique of forming composite curve is applied to analyze the effect of each building block on the temperature-enthalpy profile of the ORC heat requirement.

Wang et al. [4] did the performance analysis of double organic rankine cycle for discontinuous low temperature waste heat recovery. The optimal operation of several working fluids have been calculated by a procedure employing MATLAB and REPROP. The influence of outlet temperature of heat source on the net power output, thermal efficiency, power consumption, mass flow rate, expander outlet temperature, cycle irreversibility and exergy efficiency at a given pinch temperature difference has been employed to obtain a thermodynamic understanding of the ORC performance.

Larjola [5] suggested that electricity from industrial waste heat using high speed organic rankine cycle. In the conversion of low temperature heat into electricity the greatest efficiency is obtained in many cases by using an Organic Rankine Cycle. The ORC process may be feasible also in high temperature applications. This paper deals with an ORC design, in which a high speed oil free turbo generator feed pump is used.

Li et al. [6] did evaluation of external heat loss from a small scale expander used in organic rankine cycle. With the scaling down of the ORC, the engine shaft power is not only determined by the enthalpy drop in the expansion process but also the external heat loss from the expander. Theoretically and experimentally support in evaluating small scale expander heat loss is rare. They presented a quantitative study on the convection, radiation and conduction heat transfer from a kw-scale expander. A mathematical model is built and validated.

Quoilin et al. [7] did performance and design optimization of a low cost solar organic Rankine cycle for remote power generation. Recent interests in small scale solar thermal combined heat and power system has coincided with the demand growth for distributed electricity supplies in area poorly served by centralized power stations. One potential technical approach to meet this demand is parabolic trough solar thermal collector coupled with Organic Rankine Cycle heat engine. He also describes the design of solar organic rankine cycle being installed in Lesotho for rural electrification

purpose. The system consist of parabolic trough collectors, a storage tank, a small scale ORC engine scroll expanders. A model of each component is developed which allows sizing the different components of cycle and evaluates the performance of system. Heberle et al [8] did energy based fluid selection for a geothermal Organic Rankine Cycle for combined heat power generation. In this study the option of combined heat and power generation was considered for geothermal resources at a temperature level below 450k. Series and parallel circuits of an organic rankine cycle and additional heat generation was organized by second law analysis. The result shows that the second law efficiency of geothermal power plant can be significantly increased in comparison to power generation.

Liu et al. [9] did investigation of two stage Rankine cycle for electric power plant. A two stage Rankine cycle for power generation is presented in this paper. It is made of water steam Rankine Cycle and Organic Rankine bottoming Cycle. By using an organic fluid with density higher than water. The performance of two stage Rankine cycle operating with those different working fluids is evaluated. System efficiency can also be enhanced by introducing a regenerator for some of working fluids. Aleksandra & Borsukiewicz [10] suggested pumping work in rankine cycle and made calculation based result for the pumping work on ORC. Analysis has been carried out for 18 different organic fluids that can be used a working fluids in the subcritical ORC system. An attempt was made to find correlations between various thermo-physical properties of working fluids, specific work and power of cycle. Clemente et al. [11] proposed the energy efficiency analysis of organic rankine cycle with scroll expanders for co-generative applications. The model of scroll machine is applicable to calculate the performance of both a compressor and expander, as function of geometry of device and working fluid.

Garcia-Rodriguez et al. [12] proposed solar powered Rankine cycle for fresh water production. He also focused that on the analysis of distributed solar powered generation systems for driving a reverse osmosis desalination process. Results point out the desalination system coupled to solar powered organic rankine cycle exhibit lower specific consumption of solar energy than solar distillation. Sprousell and Depick [13] suggested the review of Rankine Cycle for internal combustion engine exhaust waste heat recovery. This paper review the history of internal combustion engine exhaust waste heat recovery focusing on organic rankine cycle since this thermodynamic cycle works well with medium grade energy of exhaust. Selection of cycle expander and working fluid are primary focus of the review. Results demonstrate a potential fuel economy improvement around 10%. Florian and Dieter [14] suggested exergy based fluid selection for a geothermal Organic Rankine Cycle for combined heat and power generation. Algieri and Morne [15] suggested the comparative energetic analysis of high temperature subcritical and transcritical Organic Rankine cycle in a biomass application in the Sibari district. The present work aims to analyze the energetic performance of ORC's for small scale applications.

Hui-tao et al. [16] did the optimization of Low temperature exhaust gas waste heat fuelled organic Rankine cycle. Cycle

parametric analysis was performed to examine the effects of thermodynamic parameters on the cycle. Kosmadakis et al. [17] suggested the parametric theoretical study of a two stage solar rankine cycle for RO distillation. The present work concerns the parametric study of an autonomous two stage solar ORC for Ro desalination. The main aim is to estimate the efficiency as well as to calculate annual mechanical energy available for desalination. J.P. Roy and Ashok Mishra [18] presented analysis of regenerative Organic Rankine Cycle (ORC), based on parametric optimization using R-123 and R-134a during superheating at a constant pressure of 2.50 MPa under realistic conditions. The aim was to select a better working fluid on the basis of obtained system efficiency, turbine work output, irreversibility rate and second law efficiency under applied fixed and variable heat source temperature conditions, R-123 has been found a better working fluid than R-134 for converting low grade heat to power. A computer program has been developed to parametrically optimize and compare the system and irreversibility ratio with increases in turbine inlet temperature (TIT) under different heat source temperature conditions to obtain the optimum operating conditions while using R-123 as the working fluid during superheating at various turbine inlet pressures for the utilization of the waste heat sources of temperatures above 150°C. The calculated results reveal that an inlet pressure of 2.70 MPa gives the maximum system efficiency, turbine work output and second law efficiency with minimum irreversibility rate, irreversibility ratio and system mass flow rate up to a TIT in the range of 165°C-250°C. W.Li et al. [19] set some initial & boundary conditions, for a mathematical model. In the analysis, three types pure fluid and one mixture were selected as working fluids and their parametric changes were calculated under different evaporating temperatures. When organic Rankine cycle (ORC) is equipped with internal heat exchanger (IHE), its parameters varies while using different working fluids. Dai Y et al. [20] did parametric optimization and comparative study of Organic Rankine Cycle for low grade waste heat recovery in saturated cycle. Karellas et al. [21] had presented a subcritical cycle and stimulated it under the same operation conditions as superheated cycle, however, the pumping pressure is kept higher than the pressure used for superheated cycle but slightly lower than the critical pressure for working fluids. V. Lemort et al. [22] presented results of an experimental study carried out on a prototype of an open-drive oil-free scroll expander integrated into an ORC working with refrigerant HCFC-123. By exploiting the overall expander performance measurements, the eight parameters of a scroll expander semi-empirical model are then identified. The model is able to compute variables of first importance such as the mass flow rate, the delivered shaft power and the discharge temperature, and secondary variables such as the supply heating-up, the exhaust cooling-down, the ambient losses, the internal leakage and the mechanical losses. The maximum deviation between the predictions by the model and the measurements is 2% for the mass flow rate, 5% for the shaft power and 3K for the discharge temperature. The validated model of the expander is finally used to quantify the different

losses and to indicate how the design of the expander might be altered to achieve better performances. This analysis pointed out that the internal leakages and, to a lesser extent, the supply pressure drop and the mechanical losses are the main losses affecting the performance of the expander. A Schuster et al. [23] used of organic working fluids organic Rankine cycle (ORC) for decentralized combined heat and power production (CHP). In the cycle process allows the use of low temperature heat sources, offering an advantageous efficiency in small scale applications. This is the reason why the number of geothermal and biomass fired power plants based on this technology have been increased within the last years. The favorable characteristics of ORC make them suitable for being integrated in applications like solar desalination with reverse osmosis system, waste heat recovery from biogas digestion plants or micro-CHP systems. In this paper, the state of the art of ORC applications will be presented together with innovative systems which have been simulated in a process simulation environment using experimental data. The results of the simulations like efficiencies, water production rates or achievable electricity production cost have been validated with experimental results. F.Herbele& D. Bruggemann [24] studied the option of combined heat and power generation was considered for geothermal resources at a temperature level below 450 K. Series and parallel circuits of an Organic Rankine Cycle (ORC) and an additional heat generation were compared by second law analysis. Depending on operating parameters criteria for the choice of the working fluid were identified. The results show that due to a combined heat and power generation, the second law efficiency of a geothermal power plant can be significantly increased in comparison to a power generation, the second law efficiency of a geothermal power plant can be significantly increased in comparison to a power generation. The most efficient concept is a series circuit with an organic working fluid that shows high critical temperatures like iso-pentane. For parallel circuits and for power generation, fluids like R227ea with low critical temperatures are to be preferred. J.P. Roy, M.K. Mishra, A. Mishra [25] carried out parametric optimization and performance analysis of a waste heat recovery system based on Organic Rankine Cycle, using R-12, R-123 and R-134a as working fluids for power generation have been studied. The cycles are compared with heat source as waste heat of flue gas at 140°C and 312 Kg/s/unit mass flow rate at the exhaust of ID fans for 4×210 MW, NTPC Ltd. Kahalgaon, India, optimized turbine inlet pressure for maximum work and efficiencies of the system along the saturated vapor line and isobaric superheating at different pressures has been carried out for the selected fluids. The results show that R-123 at corrected pressure evaluated among all the selected fluids. The Carnot efficiency for R-123 at corrected pressure evaluated under similar conditions is close to the actual efficiency. It can generate 19.09 MW with a mass flow rate of 341.16 Kg/s having a pinch point of 5°C, First law efficiency of 25.30% and the second law efficiency of 64.40%. Hence selection of an Organic Rankine Cycle with R-123 as working fluid appears to be a choice system for utilizing low-grade heat sources for

power generation.

J.Li, G.Pei, Y.Z.Li, J.Ji [26] presented a quantitative study on the convection, radiation and conduction heat transfer from a kW-scale expander. A mathematical model is built and validated. The results show that the external radiative or convective heat loss coefficient was about 3.2 or 7.0 W/m<sup>2</sup>K when the ORC operated around 100°C. Radiative and convective heat loss coefficients increased as the expander operation temperature increased. Conductive heat loss due to the connection between the expander and the support accounted for a large proportion of the heat loss. The fitting relationships between heat loss and mean temperature difference were established. It is suggested that low conductivity material be embodied in the support of expander. Mattress insulation for compact expander could be eliminated when the operation temperature is around 100°C. S. Quoilin et al. [27] studied small-scale solar thermal combined heat and power(CHP) power systems has coincided with demand growth for distributed electricity supplies in areas poorly served by centralized power stations. One potential technical approach to meeting this demand is the parabolic trough solar thermal collector coupled with an organic Rankine cycle (ORC) heat engine. The design of a solar organic Rankine cycle being installed in Lesotho for rural electrification purpose. The system consists of parabolic trough collectors, a storage tank, and a small scale ORC engine using scroll expanders. A model of each component is developed taking into account the main physical and mechanical phenomena occurring in the cycle and based on experimental data for the main key components. The model allows sizing the different components of the cycle and evaluates the performance of the system. Different working fluids are compared, and two different expansion machine configurations are simulated (single and double stage). N.Yamada, M.N.A. Mohamad, T.T. Kien [28] HFO-1234yf is a new refrigerant with a nearly zero global warming potential (GWP) and ozone depletion potential (ODP); it exhibits thermodynamic properties similar to HFC-134a. The potential if HFO-1234yf as a working fluid for organic Rankine cycle (ORC) is elucidated through a first order simulation. A fundamental thermodynamic model of ORC with five types of cycles trilateral, saturated, superheated, sub-critical, and supercritical used to compare the thermal efficiency of HFO-124yf with that of other working fluids. HFO-1234yf was found to offer a thermal efficiency that was comparable to that of HFC-134a. This paper provides a useful clearly shows the best possible thermal efficiency among the five types of cycle for various expander inlet and condensation temperatures. The highest thermal efficiency range (8.8%-11.4%) was obtained when the supercritical ORC was used at an expander inlet temperature of 170°C and condensation temperature range of 20-40°C for the given pump and expander efficiency.

F.A. Al-Sulaiman, I. Dincer, F. Hamdullahpur [29] This part of the study presents the thermo economic optimization formulations of three new trigeneration systems using organic Rankine Cycle (ORC): SOFC-trigeneration, biomass-trigeneration, and solar-trigeneration systems. A thermo-

economic modeling is employed using the specific exergy costing (SPECOC) method while the optimization performed using the Powell's method to minimize the product cost of trigeneration (combined cooling, heating, and power). The results help in understanding how to apply the thermodynamic modeling and thermoeconomic optimization to a trigeneration system.

F.A. Al-Sulaiman, I. Dincer, F. Hamadullahpur [30] studied, three new trigeneration systems are examined. These systems are SOFC-trigeneration, biomass-trigeneration, and solar-trigeneration systems. This study reveals that the maximum trigeneration-exergy efficiencies are about 38% for the SOFC-trigeneration system, 28% for the biomass-trigeneration system and 18% for the solar-trigeneration system. Moreover, the maximum cost per exergy unit for the SOFC-trigeneration system is approximately 38\$/GJ, for the biomass-trigeneration system is 26\$/GJ and for the solar-trigeneration system is 24\$/GJ. This study reveals that the solar trigeneration system offers the best thermo-economic performance among the three systems. This is because the solar-trigeneration system has the lowest cost per exergy unit. Furthermore, the solar trigeneration system has zero CO<sub>2</sub> emissions.

### 3. System Description

#### 3.1 Subcritical ORC

In the Subcritical ORC configuration of ORC system which is compared of an evaporator, an expansion device, a condenser, a pump and a cooling cycle. The condenser and the evaporator are both described as three-stage models by Quoilin and Wei. The thermodynamic processes of the subcritical ORC system When IHE is proposed, the liquid working fluid before entering the evaporator exchanges heat with the gas working fluid coming out of expander in the IHE. The liquid working fluid gets heated from T<sub>8</sub> to T<sub>19</sub> whereas the gas working fluid gets cooled.

As it is very well known that if we know any two parameters out of the four parameters T<sub>i</sub>, P<sub>i</sub>, h<sub>i</sub>, s<sub>i</sub> of the state point than the other two parameters can be determined. And for doing all these thermodynamic calculations use of E E .S. This software is easy and flexible to use and has the advantage of ready to use optimization techniques and fluid properties. It makes use of the same equation of state as used in REFPROP-NIST. This is a versatile software and a very useful tool.

#### 3.2 Supercritical ORC

In a supercritical organic Rankine cycle, the process that occurs in evaporator is a complex two phase process, simply implying that a three stage model cannot be used. However the

other facilities are same with almost no differences among them with the only difference that an evaporator is replaced by a one stage model. Due to the complexity of two phase change, there occurs a difficulty in locating the position of pinch point. In a subcritical cycle, by default the pinch point is assumed between point 9 and point 13, which in most cases is tenable, and the added condition that the temperature difference between T<sub>11</sub> and T<sub>1</sub> is too large. However, in a supercritical cycle, trends of working fluid evaporation progress and constant pressure lines of the heat source are similar, hence it becomes difficult to identify the pinch point position qualitatively. Some previous studies did their simulation by assuming the outlet temperature of the heat source or by assuming the location of pinch point, or setting and defining effectiveness of internal heat exchanger at a constant value of  $\epsilon$ . It simplified the calculation while it would also lead to the consequence that the temperature difference of the pinch point would be less or more than the value which is already set, which is not in conformity with the real condition in heat exchanger. The given minimum heat transfer temperature difference  $\Delta T_{pp}$  is used for calculating the effectiveness of Internal heat exchanger i.e.  $\epsilon$ , but the derivation of reversing process is not real. Here, an iteration method is suggested through which the pinch point position in the supercritical cycle can be located. Once  $\Delta T_e$  is set, the working fluid's evaporation zone is divided equally to N number of parts in the direction of entropy. The lowering of the outlet temperature of heat source is used to find the minimum gap between the working fluid evaporation isobar and the heat source isobar. When this equals  $\Delta T_{pp}$ , the outlet temperature can be determined and the position of pinch point is N. Fig. 3.5 demonstrates this method and Fig. 3.6 is the flow diagram which is written as per this method. The application of this approach includes the calculation of outlet temperature of heat source in supercritical systems, which strictly suggests that  $\Delta T_{pp}$  should be at the set value of 10°C.

#### 3.3 Global Model

The system safety, economic efficiency of ORC system and environmental protection is greatly influenced by the choice of working fluids. The widely used fluids includes the applicable fluids with good thermodynamics, safety and economic characteristics, environmental protection, such as fluids with low liquid specific heat, viscosity, toxicity, flammability, ozone depletion potential, global warming, and price. Based upon above criterion, the working fluid R600 and R123 are chosen for subcritical and supercritical cases separately. The basic environmental and thermodynamic properties of the above mentioned fluids are shown in Table 2.

Table 2: Basic thermodynamic and environmental properties of R123 and R600

Working Fluid	T <sub>cr</sub> (°C)	P <sub>cr</sub> (MPa)	T <sub>fp</sub> (°C)	T <sub>bp</sub> (°C)	Safety	ODP	GWP
R123	183.7	3.668	-107.2	27379	B1	0.012	120
R600	152	3.796	-138.3	-0.5208	A3	0	-20

The following assumptions are made in the analysis in order to simplify the computing and complicity which are neither the key points not they affect the accuracy of results coming in the model suggested.

- (i) The whole system is under equilibrium state.
- (ii) The specific heat of the hot stream is replaced with one the one of hot air.
- (iii) The heat losses and leakages through the pipeline and components are ignored.

Some unchanged parameters involved in the calculations are shown in Table 3

Table 3: Assumptions of Streams and Components

Parameter	Sign	Unit	Value
Environment temperature	T0	°C	15
Low Grade Heat flow temperature	Th,in	°C	200
Cooling water temperature	Tc,in	°C	15
Condensation Temperature	Tcond	°C	30
Low Grade Heat Mass Flow Rate	qv,h	Kg/s	1
Superheat Degree	Tsup	°C	3
Degree of Subcooling	Tsub	°C	1
Pinch Point	ΔTpp	°C	10
Temperature difference at hot stream inlet of Evaporator	ΔTe	°C	15
Acid Dew Point	Tad	°C	110
Adiabatic efficiency of Expander	ηT,i	1	0.65
Mechanical Efficiency of Expander	ηT,m	1	0.9
Working fluid pump Adiabatic efficiency	ηis	1	0.8
Working fluid pump Mechanical efficiency	ηPm	1	0.9
Efficiency of cyclic pump	ηcpu	1	0.8
Total circulation loop Flow resistance	dPif	kPa	600
Total resistance at condenser cooling water side	dPcf	kPa	300

#### 4. Thermodynamic Modelling

In the thermodynamic modelling the following set of mathematical equations are used analysis for computing system thermal performances as given below.

##### 4.1 Energy Analysis

The first law of thermodynamics is the basis for the energy analysis. The final results includes the net output and the thermal efficiency. As already mentioned in the assumptions, their value is dependent only on evaporation pressure i.e.  $P_{\text{evap}} = P_1 = P_8$ . Following are the set of equations for different components.

##### 4.2 Subcritical ORC

Since all the used formulas in supercritical case are same as that of the subcritical case hence suggesting that the energy analysis in both the cases are almost same. At the critical point

the specific heat of working fluid changes dramatically in case of supercritical cycle. These variation characteristics are shown in the temperature range that is considered in simulation which is assumed constant in case of subcritical cycle. Then there is required a modification in the cycle to take these variations into account. The following equation represents the heat between two streams in internal heat exchanger.

$$Q_{\text{IHE}} = m_h \cdot (h_{19} - h_8) = m_f \cdot (h_2 - h_{20})$$

The following situation occurs when minimum heat transfer temperature difference i.e.  $\Delta T_{\text{pp}}$  is taken into account which in turn depends on which of the two streams in internal heat exchanger has smaller heat capacity.

##### 4.3 Exergy Analysis

The drawback of energy analysis is that the conversion of energy of evaporator and condenser could not be done. Exergy analysis is a energy conversion coefficient that focuses on quantity as well as quality of energy, and this parameter more profoundly tells the essence of losses and energy conversion as compared to energy analysis. The exergy destruction in each component can also be calculated by this analysis.

The exergy analysis can be done by calculating the specific flow exergy at exit and entry of sources and also at each state point in cycle. The following expression gives the quantity: Where the subscript 0 represents the environmental conditions which are considered to be 15°C and atmospheric pressure. Following are the equations for different components.

#### 5. Result and Discussion

In this study, the simulation of subcritical and supercritical organic Rankine cycle system with or without internal heat exchanger using respectively R123 and R600 is done which illustrates the impacts of internal heat exchanger on ORC systems. The mass flow rate taken into account for analysis is 1 kg/s and the heat source temperature is taken as 200°C. The temperature difference of 10°C is set as the minimum heat transfer temperature difference of heat exchanger. When a supercritical system is modeled, a modified method for maximum heat exchanger in an internal heat exchanger is given, which is attributed by the fact that in the supercritical system when working conditions lies near critical point conditions of the working fluid, then the specific heat of the fluid should not be considered as constant, which is different from subcritical system temperature of heat source in subcritical system. Also, a new approach is suggested for calculating the location of pinch point and outlet temperature of heat source in subcritical system which specifies that the minimum temperature difference of evaporator for heat transfer should be equal to the set value of 10°C. And, when acid dew point is considered, it is observed that the internal heat exchanger improves the net output and justifies the applicability of system.

## 6. Conclusion

The following conclusions were drawn from present investigation.

- (i) The internal heat exchanger always increases the exergy efficiency, thermal efficiency, and the outlet temperature of heat source in subcritical ORC system. However, there is no change in the net output of the system which remains the same.
- (ii) The supercritical ORC system consists of a Range C in which the thermal efficiency, outlet temperature of heat source and exergy efficiency improves by the application of internal heat exchanger, keeping the system net output to be the same. The system performance degrades when an internal heat exchanger is used outside of this range.
- (iii) When acid dew point  $T_{ad}$  is considered, the net output of system is increased indirectly in a subcritical system on the application of internal heat exchanger while in supercritical system, the evaporation pressure starts obeying the rule  $T_{h,out} > T_{ad}$ . It is found that the applicability of system is strengthened by the application of IHE.
- (iv) Comprehensive analysis of different upcoming working fluids comparison is to be done in both subcritical and supercritical systems that are equipped with IHE.
- (v) More economical indicators like UA values and heat exchanger area is to be investigated.

## References

- [1] Serrano J.R., Dolz V., Novella R., Garcia A., [2011]. HD Diesel engine equipped with a bottoming Rankine cycle as a waste heat recovery system. *Applied Thermal Engineering* 36, page- 279-287.
- [2] Wang X. D., Zhao L., Wang J.L., Zhang W.Z., Zhao X.Z., W.Wu. 2009, Performance evaluation of low temperature Solar Rankine Cycle System utilizing R245fa. *Solar Energy* 84(2010), 353-364.
- [3] Di Genova Kevinj., Botros Barbara B, Brisson J.G., [2012] Method for customizing on Organic rankine cycle to a complex heat source for efficient energy conversion, demonstrated on Fischer Tropsch Plant. *Applied Energy* 102, page-746-754.
- [4] Wang Dongxiang, Ling Xiang, PengHao, [2012]. Performance Analysis of double organic rankine cycle for discontinuous low temperature waste heat recovery. *Applied thermal Engineering* 48, page-63-71.
- [5] Larjola J., [1994], Electricity from industrial waste heat using high speed organic rankine cycle. *International journal of Production Economics* 41, page-227-235.
- [6] Li Jing., Pei Gang, Li Yumhuli, JiJie., [2012]. Evaluation of External heat loss from small scale expander used in organic rankine cycle. *Applied Thermal Engineering* 31, page-2694-2701.
- [7] Quilin S., Orosz M., Hemond H., Lemort V., [2012]. Performance and design optimization of Low cost solar organic rankine cycle for remote power generation. *Solar Energy* 85, page-955-966.
- [8] Herberle Florian, Bruggemann Dieter, [2010]. Exergy based fluid selection for geothermal organic rankine cycle for combined heat and power generation. *Applied Thermal Engineering* 30, page-820-880.
- [9] Liu Bo., Riviere Philippe, Coquelet Christopher, Gicquel Renaud, David Frank, [2012]. Investigation of a two stage Rankine cycle for Electric power Plants. *Applied energy* 100, page-285-294.
- [10] Borsukiewicz- Gozdur Aleksandra, [2013]. Pumping work in organic Rankine cycle. *Applied thermal engineering* 51, page-781-786.
- [11] Clemente Stefnio, Michel Diego, Mauro Reini, TaccaoniRodolf, [2012]. Energy Efficiency analysis of organic rankine cycle with scroll expander. *Applied energy* 97, page-792-801.
- [12] Garcia Lourdes Rodriguez, Austin M.Delgado-Torres, [2007]. Solar powered Rankine cycle for fresh water production. *Desalination* 212, page-319-327.
- [13] Sprousell Charles, Depicl Christopher, [2013]. Review of organic Rankine cycle for internal combustion engine Exhaust waste heat recovery. *Applied Thermal Engineering* 51, page-711-722.
- [14] Herberle Florian, Bruggemann Dieter, [2010]. Exergy based fluid selection for Geothermal Organic Rankine cycle for combined heat and power generation. *Applied Thermal Engineering* 30, page-1326-1332.
- [15] Algeri Angelo, Morrone Pietropaolo, [2012]. Comparative energetic analysis of high temperature sub-critical and transcritical organic rankine cycle. *Applied Thermal Engineering* 36, page-236-244.
- [16] Hui-tao Wang, Hu Wang, Zhu-ming Zhang, 2011. Optimization of low temperature exhaust gas waste heat fuelled organic rankine cycle. *Journal of Iron and Steel Research, International*, Vol-19, No.6, page-30-36.
- [17] Kosmadakis G, Manolakos D, Papadakis G, [2010]. Parametric Theoretical study of a two stage solar organic rankine cycle for RO desalination, *Renewable Energy* 35, page-989-996.
- [18] P.J. Mago, K.K. Srinivasan, L.M. Chamra, C. Simayaji, [2008] An examination of exergy destruction in organic rankine cycles, *Int. J. Energy Res* 32, page-926-938.
- [19] W. Li, X. Feng, L.J. Yu, J. Xu, [2011] Effects of evaporating temperature and internal heat exchanger on organic Rankine cycle, *Appl. Therm. Eng.* 31, page- 4014-4023.
- [20] Y.P. Dai, J.f. Wang, L. Gao, [2009] Parametric optimization and comparative study of organic Rankine cycle (ORC) for low grade waste heat recovery, *Energy Convers, Manag.* 50, page-576-582.
- [21] Karellas S, Schuster A., [2008] Supercritical fluid parameter in organic Rankine cycle Applications. *International Journal of Thermodynamics*, 11(3), page-101-8.
- [22] V. Lemort, S. Quoilin, C. Cuevas, J. Lebrun, [2009] Testing and modeling a scroll expander integrated into an organic Rankine cycle, *Appl. Therm. Engg.* 29, page- 3094-3102.
- [23] A. Schuster, S. Karellas, E. Kakaras, H. Spliethoff, [2009] Energetic and economic investigation of organic rankine cycle applications, *Appl. Therm. Eng.* 29, page-1809-1817.
- [24] F. Heberle, D. Bruggemann, [2010] Exergy based fluid selection for a geothermal organic Rankine cycle for combined heat and power generation, *Appl. Therm. Eng.* 30, page-1326-1332.
- [25] J.P. Roy, M.K. Mishra, A. Mishra, [2010] Parametric optimization and performance analysis of a waste heat recovery system using organic Rankine cycle, *Energy* 35, page-5049-5062.
- [26] J. Li, G. Pei, Y.Z. Li, J. Ji, [2011] Evaluation of external heat loss from a small-scale expander used in organic Rankine cycle, *Appl. Therm. Eng.* 31, page-2694-2701.
- [27] S. Quoilin, R. Aumann, A. Grill, A. Schuster, V. Lemort, H. Spliethoff, [2011] Dynamic modeling and optimal control strategy of waste heat recovery organic Rankine cycle, *Appl. Energy.* 88, page-2183-2190.
- [28] N. Yamada, M.N.A. Mohammad, T.T. Kien, [2012] Study on thermal efficiency of low to medium temperature organic Rankine cycles using HFO-1234yf, *Renew. Energy* 41, page-368-375.
- [29] F.A. Al-Sulaiman, I. Dincer, F. Hamdullahpur, [2013] Thermo-economic optimization of three trigeneration systems using organic Rankine cycles: part 1 – formulations, *Energy Convers. Manag.* 69, page-199-208.
- [30] F.A. Al-Sulaiman, I. Dincer, F. Hamdullahpur, [2013] Thermo-economic optimization of three trigeneration systems using organic Rankine cycles: part II – applications, *Energy Convers. Manag.* 69, page-209-216.