THERMAL CYCLES OF HEAT RECOVERY POWER PLANTS

Tangellapalli Srinivas

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Thermal Cycles of Heat Recovery Power Plants

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FOREWORD 1

It is an honour for me to write the foreword for the book titled “Thermal Cycles of Heat Recovery Power Plants,” written by Dr. T Srinivas. The scope of the book is in the area of heat recovery power generation and thermal cycle analysis. The book covers various heat recovery power generation systems and thermodynamic cycle analysis. Given the growing global energy demand, there is a need to improve power generation efficiency and to conserve energy resources. Global warming and the need to reduce greenhouse gas emissions demands higher efficiency fossil fuel-based power plants. The waste heat recovery and utilization will help to reduce greenhouse gas emissions. The cycle analysis plays a dominant role in understanding the heat recovery based power plants, including the performance. The book covers various thermal cycles and their analysis, including the performance of heat recovery based systems.

Srinivas is a well-known researcher in the areas of thermal power generation, combined cycle and cogeneration systems, waste heat recovery, solar energy, and exergy analysis. He has published extensively in journals and conference proceedings as an author and also with research collaborators. We have worked together on research projects in thermal power generation, waste heat recovery, and solar energy and published them in reputed journals and conference proceedings.

The “Thermal Cycles of Heat Recovery Power Plants” book covers the latest advances in heat recovery power generation systems, various thermal cycles, and analysis, including recent advances. The book incorporates recent advances in research and developments in heat recovery based power generation systems. I am confident that the book will be very useful to senior undergraduate level students, graduate-level students, researchers working in the area of thermal power generation and waste heat recovery power generation, and for practicing engineers in the area of thermal power generation, waste heat recovery, and energy management.

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FOREWORD 2

The power generation from the waste heat recovery is equivalent to the power from the renewable energy sources as it does not generate any new or additional carbon dioxide to the environment. Therefore, these power plants are also eligible to claim the carbon credits as per the policy norms. I wish this book on the power thermal cycle of heat recovery power plants nurtures new ideas of power plants to tap the waste heat recovery. This book deals with the thermodynamic analysis of very important vapour power cycles such as organic Rankine cycle, organic flash cycle, Kalina cycle, steam Rankine cycle, and steam flash cycle from the modelling to the optimization of performance parameters and highlighting the challenges and opportunities. The latest power cycles, including the Kalina cycle, organic flash cycle, and steam flash cycle, are thoroughly analysed with exhaustive models and examples. The book also covers important practical aspects of the power cycles with detailed case studies, which may be very useful for the students. I know that Dr. T. Srinivas is also an author of ‘Flexible Kalina Cycle Systems’, which is focused on cooling cogeneration cycle based on Kalina cycle working principle. The chapter on comparison of the power cycles based on various thermodynamic characteristics may be very useful to the students and researchers. I hope this book contributes to the understanding of the power cycle’s concepts, design, and development of new plants to the students, scholars, faculty, and practicing engineers for innovative developments.

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PREFACE

Worldwide many thermal industries are working without tapping the valuable waste heat into a useful form. Electricity is one of the most extensively used commodities in the world. The existing and futuristic power plant configurations and its characteristics suitable to a waste heat recovery (WHR) are discussed in the book. Novel power plant configurations are developed and elaborated from modelling to the optimization through the simulation. Five different power plants configurations, suitable to heat recovery are presented *viz.* organic Rankine cycle (ORC), organic flash cycle (OFC), Kalina cycle (KC) steam Rankine cycle (SRC) and steam flash cycle (SFC). Out of these power plant layouts, flash cycle (FC) has been recommended because of its adoptability to the heat recovery. The novel flash cycle, which is different from the current geothermal power plant is detailed to augment the heat recovery and power with organic fluid system and steam system. In a power plant, the source temperature may fall below the critical temperature of the fluid or above it. The performance characteristics of these power plants differ with the working fluid and state of heat source, *i.e.*, below or above the critical temperature. Separate performance characteristics and correlations are developed in these two regions for all the selected fluids. The selected working fluids in the heat recovery power plants are R123, R124, R134a, R245fa, R717 and R407C. In FC, the liquid is flashed from high pressure to low pressure at the exit of heat recovery's economizer. The vapour is separated from the process and used in turbine for power augmentation. However, the handling of additional fluid in boiler increases the pump capacity and heat recovery. Therefore, a drop in thermal efficiency has been observed. FC plants are well justified by comparing the existing power plants with its higher production rate. A case study related to cement factory's heat recovery has been presented to understand the power plant nature with heat recovery. The cement factory demands 15 MW for its functioning and the case study showed that the WHR is capable of producing the self-generation to meet the load. A lower heat recovery pressure is suggested for maximum power. Second case study is at a 7.7 MW power plant operating under SFC. The theoretical results are validated with a cement factory's case studies with SRC and SFC. The mathematical simulation has been extended to solve 'n' flashers in SFC. Finally, OFC and SFC are recommended in place of ORC and SRC for maximum output.

Organic flash cycle or steam flash cycle are not reported in the available books in the area of power industry. This book companions the undergraduate and post graduate students of mechanical, electrical and similar streams, power plant engineers, practising engineers, research scholars, faculty and plant trainees in the field of power generation. Latest power plant configurations, selection of working fluids to suit the heat recovery temperature and novel flashing cycle in place of organic Rankine cycle and steam Rankine cycle are the key features of this book.

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My first lecture in my teaching profession is on thermal power plants at AANM and VVRSR Polytechnic, Gudlavalleru India. Thanks to the institute for creating such wonderful learning platform through teaching. I had an opportunity to visit Vijayawada Thermal Power Plant (VTPS) with my students from Gudlavalleru Engineering College, India. The plant's staff instructed the practical methods and highlighted the thermal power plant technology. My sincere thanks to the management, all staff members and specially Mr. Muthaiah Chary, Engineer - Maintenance, VTPS for his energetic guidelines and guiding the complete plant processes and components. The industry supports from VTPS, LANCO Power, GMR Energy, India Cements and Sagar Cements enhanced the understanding and nurtured the innovation in power generation technologies with the case studies. I thank all the industrial support for playing a key role in the development of the thermal cycles of heat recovery power plants. I recognize my research scholar, Dr. Pradeep Varma for conducting the valuable case studies at cement factories to formulate the new ideas of power generation through the waste heat recovery.

Thanks to the whole team of VIT University, Vellore, for providing the atmosphere and supporting to shape the fundamental ideas into reality. My sincere thanks to Prof. Lalit Kumar Awasthi, Director, Dr. B.R. Ambedkar, National Institute of Technology Jalandhar for providing the facilities and support to shape this book. My hearty salutations to faculty, non-teaching staff, students and scholars of department of mechanical engineering, NIT Jalandhar for continuous encouragement and providing the things.

My honest gratitude to Dr. P.K. Nag, Professor, IIT Kharagpur for inspiring and advising on thermodynamics applied to various thermal power plants. I am extremely happy to express my deepest gratitude to my PhD guide, Dr. AVSSKS Gupta, Professor, JNT University, Hyderabad for sculpturing me in the field of thermal engineering. It is my fortune to associate with the dynamic and energetic Professor and Guide Dr. BV Reddy, Ontario Tech University, Canada. I wish to express my gratitude to Dr. Reddy for his motivation and backing support. I am happy to convey my thanks to all my research scholars, faculty, staff and students to be a part of my research work. My special thanks to all the staff from CO_2 Research and Green Technologies Centre, VIT University, Vellore for assisting in plant development, erection and testing processes at the laboratory level.

I would like to express my deep sense of gratitude and respect to parents who fashioned my hard work and strong determination since my childhood. My heart felt gratitude to my lovely wife, Kavitha Devi, dearest elder son Rahul and dearest younger son Jignesh; without their regular support and boosting, I cannot do anything.

Finally, thanks to all who were involved in this work, directly or indirectly, in shaping this book to reach its fruitful form.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The author declares no conflict of interest, financial or otherwise.

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CHAPTER 1

Introduction on Heat Recovery Power Plants

Abstract: This chapter overviews the heat recovery with power generation plants. The significance of captive power plants has been highlighted. Different heat recovery arrangements as per the category of thermal power cycle have been discussed. The power plant layouts of organic Rankine cycle (ORC), organic flash cycle (OFC), Kalina cycle (KC), steam Rankine cycle (SRC) and steam flash cycle (SFC) are deliberated. The subsequent chapters are focused on the detailed study of thermal cycles of heat recovery power plants.

Keywords: Bottoming cycle, Captive power plant, Energy efficiency, Energy scenario, Thermal power cycles, Topping cycle.

POWER GENERATION FROM WASTE HEAT RECOVERY

Is waste heat recovery (WHR) a renewable energy? The USA framework of climate change declared WHR power as green energy. These projects can claim the carbon credits for earning. The carbon credits are sanctioned for CO_2 reduction but not for renewable energy generation. Energy is capital for any country's development. A lot of waste heat is dumped on earth without dropping its temperature. This book is focused on construction, working, and description of power generation technologies using waste heat recovery. Power generation from fossil fuel causes environmental issues such as carbon dioxide emissions and thermal pollution. The electricity installed capacity of a nation is the sum of utility capacity and captive power capacity. The utility plants are the grid connected power plants. The captive power plants are the decentralized power plants, operating mostly on off-grid mode. The decentralized power generation using renewable technology is one of the promising solutions to address environmental pollution. Apart from the renewable energy sources, power from waste heat recovery is an attractive solution for self-generation of electricity without creating additional carbon dioxide in the environment. Since there is no investment in energy sources such as fuel or renewable energy technologies, the WHR power plants are doing a large business in the power market.

The major consumer of electricity is the industry, followed by domestic, agriculture, commercial, traction, railways, and others.

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Since the thermal industries handle heat, they can switch into heat and power, *i.e.* , cogeneration plants. Concrete measures are to be taken for the effective use of waste heat from industries for power generation. Depending on the size of the power plant, these power plants may be operated either captive mode (small capacity) or gird connection mode (high capacity). If the plant capacity is high, the excess amount of electricity can be supplied to the grid. In process industries a lot of hot flue gases are generated from kilns, furnaces and boilers. If effective utilization of those flue gases is done by using proper technology, a considerable amount of energy and money can be saved. The major part of the electricity generation is from conventional sources of energy, *viz.* coal, oil, and natural gas. However, they are exhaustive and harmful to society and the environment. The power from waste heat is one of the opportunity to this challenge. Waste heat recovery is a heat exchanger, which permits the transfer of heat from the waste hot fluid to the working fluid of the power plant. Waste heat recovery units are generally used in cogeneration plants where the outputs consist of power and process heat.

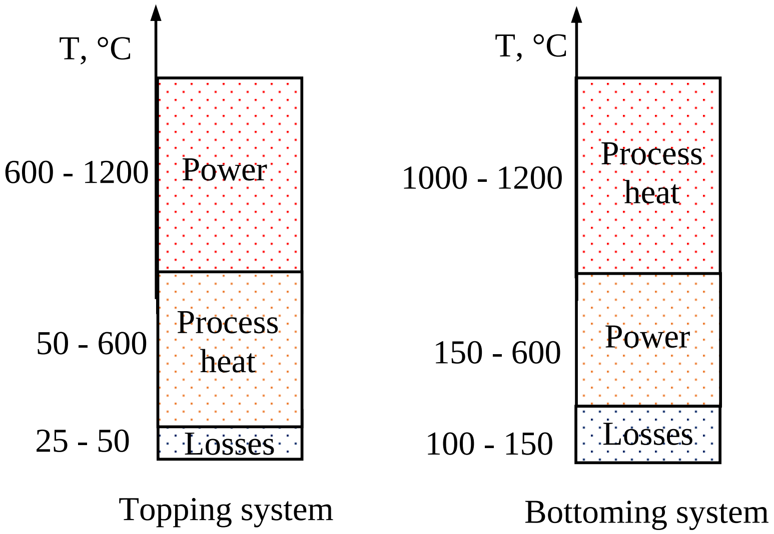

Fig. (1). Captive power through either topping cycle or bottoming cycle operation.

With reference to the position or location of the power cycle in cogeneration, the captive power plants are classified into two *viz.*, topping system and bottoming system. (Fig. **1**) differentiates the topping system and bottoming system with reference to the relative temperature of power and process heat. In a topping system, the high temperature fluid (exhaust gases, steam) drives an engine to produce electricity. In contrast, low temperature heat is used for thermal processes or space heating (or cooling). In a bottoming system, the high temperature heat is first produced for a process (*e.g.*, in a furnace of a steel mill or of glass-works, in a cement kiln). Later the hot gases are used either directly to drive a gas turbine generator if their pressure is adequate, or indirectly to produce steam in a heat recovery boiler, which drives a steam-turbine generator. In the topping system, the fuel is fired mainly to a power plant. Therefore they can not avail the benefit of carbon credits. The bottom system uses waste industrial heat without creating additional emissions, so, these plants can claim the carbon credits.

In this book, waste heat from a cement factory has been selected to develop the power plants. Therefore, the power plant cycles are bottoming systems. The studied power plant cycles are organic Rankine cycle (ORC), organic flash cycle (OFC), Kalina cycle (KC), steam Rankine cycle (SRC), and steam flash cycle (SFC).

The working fluid used in a power plant may be the single fluid system or multi-fluid system. In a single fluid system, a pure substance of working fluid such as water or R123 is used. In a binary fluid system, two working fluids are used together to get the benefit of variable temperature during the phase change. For example, in KC, ammonia and water mixture is used as a working fluid. During the processes of KC, the mixing ratio or concentration of working fluid changes from one state to other state. The mixture of ammonia and water is known as a zeotropic mixture. The zeotropic mixture can be separated by heating and absorbed (mixed) by cooling.

Fig. (**2**) shows the temperature-heat transfer profile of the heat recovery system used in a power plant. In a single fluid plant such as ORC and SRC, the saturation temperature of the working fluid is fixed in the evaporator (Fig. **2a**). The gas temperature is controlled by a constraint called as pinch point (PP). PP ensures the heat transfer from high temperature to low temperature fluid. Approach point (AP) is used between economizer and evaporator to avoid the sudden transition from liquid to vapour. In a binary fluid system, the fluid temperature is variable during the phase change (Fig. **2b**). In KC, the boiling starts at bubble point temperature (BPT) and ends with dew point temperature (DPT) in an evaporator. If the heat recovery is used for steam generation in an SRC or SFC, it is called a heat recovery steam generator (HRSG). If the vapour is generated in a heat exchanger, it is known as a heat recovery vapour generator (HRVG). In ORC, OFC, and KC, the heat exchanger is HRVG. A typical combined cycle power plant use HRSG between the topping cycle (gas power plant) and the bottoming cycle (steam power plant). In the Brayton cycle, the gas turbine inlet temperature is high with the firing of fuel in the gas turbine combustion chamber (GTCC). Therefore, a multi-pressure HRSG is used to suit the high temperature gas. Dual

CHAPTER 2

History of Heat Recovery Power Plants

Abstract: The present scenario of captive power generation has been outlined with the challenges and the future steps to be implemented. The developments of conventional and the latest power plants are presented. The literature is focused on organic Rankine cycle (ORC), organic flash cycle (OFC), Kalina cycle (KC), steam Rankine cycle (SRC), and steam flash cycle (SFC). The research gap is identified and highlighted the scope for future developments.

Keywords: Flash cycle, Kalina cycle, Organic rankine cycle, Thermal power plant, Waste heat recovery.

INTRODUCTION

World energy consumption is increasing drastically and leading to non-bearable level of carbon dioxide in the atmosphere. Environmental organizations are taking actions to measure and control greenhouse gas emissions. To control these greenhouse gases, the buildings and industries may generate their own electricity to decrease the grid load. Obviously, the technology is to be shifted from the use of conventional energy sources to non-conventional energy sources such as solar, biomass, solar thermal, solar photo-voltaic, geothermal and hydro, *etc.* The use of fossil fuels to be avoided for transportation and space heating and similar. The decentralized power section to be improved [1].

Waste heat recovery (WHR) is a heat exchanger used to transfer the heat from a high temperature fluid to low temperature fluid for the purpose of energy conversion, especially power generation. Captive power plants can be operated with the source of renewable energies, industrial waste, or fuel firing. It can be operated on grid connection or off-grid mode. The waste heat may be taped from the industrial hot gas, diesel engine exhaust, hot water from a process industry such as steel cooling, and steam from cooling towers. WHR may be designed as recuperators, regenerators, heat pipe exchangers, thermal wheels, economizers, or heat pumps. In a conventional power plant, one-third of the fuel energy is converted into electricity, and the rest of two-third is wasted and thrown on the earth. It leads to global warming and environmental disorder.

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There is a need to develop energy conversion technologies to tap the waste heat at the low temperature range. Industries handling a considerable amount of heat have a great potential for self-generation power through the recovery of waste heat. The production of electricity using this root is the most economical option compared to the direct fuel-fired plant. To meet the growing energy demand, the available best options are waste heat recovery and renewable energy technologies. Renewable energy technologies are costly and need time for complete marketing. Therefore, heat recovery is the immediately available and feasible solution for power generation without much investment and emission. The review has been conducted to understand the development and identify a suitable technology to tap the potential resources with power plant configurations and working fluids. WHR also can be used for refrigeration and air conditioning (A/C) using vapour absorption refrigeration (VAR) principle. The power and cooling cycles can be combined to form a new cycle for power and cooling. Cooling cogeneration cycle is one such example where power and cooling can be generated from a single cycle.

ORGANIC RANKINE CYCLE

The development of the infra-structure field raised the demand for cement factories. From the cement factories, nearly 40% of the energy is in the form of waste heat [2]. Chandra and Palley [3] suggested organic Rankine cycle (ORC) for the low temperature heat recovery and steam Rankine cycle (SRC) for the high temperature heat recovery of the cement factory after the process heat for cement production. Chen *et al.* [4] studied the ORC with 35 working fluids and concluded the suitable fluids, which are isentropic and dry fluids. In isentropic fluids, the saturated vapour line on the temperature-specific entropy diagram is nearly vertical, and its slope is zero. The slope of the dry fluids is positive, *i.e.*, the saturated vapour line bends towards the right. Water is a wet fluid, and its slope is negative. Bao and Zhao [5] recommended radial inward flow turbine to ORC for the highest isentropic efficiency. They also gave the guidelines to select the prime movers to ORC based on the power plant capacity. They recommended radial flow turbine for large size power plants, positive displacement turbine for medium capacity, and scroll expander for small size power plants. Mago *et al.* [6] worked on regenerative ORC and proved the benefits of this cycle over the ORC without a regenerator. Sun and Li [7] analysed the ORC plant's heat supply temperature with a change in working fluids. The working fluid plays an important role in the process conditions and performance of the ORC plant. The selection of working fluid is a big task in ORC design. Frutiger *et al.* [8] studied 15 working fluids and developed a method to select the suitable working fluid for ORC, Table **1** lists the thermal efficiency of few ORC plants with the source temperature and working fluid. The reported thermal efficiencies are proportional to the supply temperature. Since CO_2 and ethanol plant's temperature is high, the thermal efficiencies are also showing more.

ORGANIC FLASH CYCLE

Organic flash cycle (OFC) is the latest cycle and modified version of the ORC. The OFC presented in this book is different from the geothermal flash cycle. In the conventional flash cycle, complete liquid is subjected to the flashing without undergoing to evaporation and superheating. The reported OFC presented in this book consists of evaporator and superheater and more efficiency and power compared to the traditional flash cycle. Dagdas [21] focused on the flash pressures in a geothermal power plant having the working fluid of steam. Lai and Fischer [22] demonstrated the power augmentation of the flash cycle over ORC. Varma and Srinivas [23] highlighted the power augmentation of OFC over the ORC under the same energy supply conditions. Muhammad *et al.* [24] developed ORC with 1 kW capacity and R245fa fluid. The experiment resulted in maximum thermal efficiency of 5.75%, with 77.74% of the maximum expander's isentropic efficiency. Recently Witanowski *et al.* [25] optimized ORC turbine with toluene fluid with a focus on stator and rotor profile variables, rotor blade twist angle, circumferential lean, and axial sweep angles. The total static efficiency of the ORC turbine is gained by 2.8% from 77.8% to 80.6%.

Table 1. Summary of few ORC plant's performances with working fluid and source temperature.

Authors	Heat Source	Temperature, °C	Thermal Efficiency, %
Yamamoto *et al.* [9]	R123	70	11.0
Lei *et al.* [10]	R123	120	8.0
Lee *et al.* [11]	R245fa	115	6.0
Hu *et al.* [12]	R245fa	95	4.0
White and Sayma [13]	R245fa	105	8.0
Wei *et al.* [14]	R245fa	350	9.5
Yamada *et al.* [15]	R245fa	90	2.0
Yamaguchi *et al.* [16]	CO_2	200	25.0
Chen *et al.* [17]	CO_2	140	9.0
Hsieh *et al.* [18]	R218	100	5.5
Galindo *et al.* [19]	Ethanol	245	22.7
Lu *et al.* [20]	Zeotropic mixture	140	10.5

CHAPTER 3

Basic Thermodynamics of Heat Recovery Power Plants

Abstract: The basics of thermodynamics required to evaluate a thermal power plant have been summarized. The first law of thermodynamics and the second law of thermodynamics are overviewed to solve the power plant in view of energy analysis and exergy analysis. The chemical reactions with solutions are explained to understand the solid fuel firing in a typical furnace in a power plant.

Keywords: Combustion of fuels, Exergy, First law of thermodynamics, Second law of thermodynamics.

INTRODUCTION

Thermodynamics is the science of energy conversion with framed laws and regulations. In thermodynamics, heat and work are the focused energies. It plays a key role in planning and organizing a thermal system before its making. It also develops the optimum process conditions for the efficient operation of a thermal power plant. Nature has a tremendous amount of energy. The energy always tries to convert from one form to another form. Thermodynamics deals with these energy interactions in a systematic way with reference to certain rules called thermodynamic laws. Sadi Carnot, the father of thermodynamics, developed a benchmark heat engine called Carnot engine and made a goal for a thermal power plant. He also developed many theories that are more relevant to a thermal power plant. The complete thermodynamics study includes four 'E's *viz.* energy, exergy, economics, and environment. The thermodynamics laws *viz.* zero, first, second, and third are designed based on logic and common sense.

THERMODYNAMIC SYSTEM

Thermodynamic system is a prescribed region with finite matter, confined by walls which separate it from the surrondings. A typical thermal power plant consists of four thermodynamic systems *viz.* turbine, condenser, pump, and boiler. The feedwater is heated with a heat source and turned into superheated steam. In

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the condenser, the vapour is condensed into a saturated liquid state by air circulation or water circulation. The power plant handles various fluid lines such as fuel, air, cooling oil, steam, circulating water, feedwater, and hot gas. Similarly, the systems also involve heat and work transfers. Therefore, the thermodynamic system can be described with mass and energy transactions. To understand the nature of system, it is required to define the terminology used in the system, and they are surroundings, boundary, control surface, control volume, *etc.* The space outside the system is called as surroundings. Boundary is the enclosure that separates the system from the surroundings. The boundary may be real or imaginary. It is a stationary boundary or moving boundary. The system and its surroundings together are called as the universe. Thermodynamic systems can be grouped into an open system, closed system, and isolated system.

In an open system, the mass and energy cross the boundary. In this system, the fixed region in space is the control volume, and the surface of the control volume is called as the control surface. For example, in a steam boiler, feedwater enters into the system and leaves as a superheated steam (mass transfer) by absorbing heat (energy interaction). Compresser, turbine, nozzle, diffuser, steam engine, boiler, *etc.*, are the open systems. If a system allows mass without energy transfer, such as steam flowing in an insulated pipe, that is also an open system. In this case, even though there are no energies crossing the boundary, because of insulated pipe, the fluid carries energy along with the flow, which is called kinetic energy. In addition to this kinetic energy, it also possesses flow work. The frictional resistance in the insulated pipe drops the fluid velocity. So within the control volume, the energy exchange occurs without crossing the control surface or boundary. Therefore a system with mass flow, but without work and heat flow, can be treated as an open system. A system is called a closed system if it does not allow the matter to enter or leave and the energy (heat and work) across its boundary. Examples are gas enclosed in a cylinder, water stored in a container, electronic device, *etc.* In an isolated system, neither mass nor energy transfers across its boundary. Examples of an isolated system are thermos flask and universe. The system and surroundings together form an isolated system.

THERMODYNAMIC PROPERTY

Thermodynamic properties of a system are the measurable characteristics describing the system's nature. It is independent of the nature of the process and depends only on the state or condition. Therefore, the property is a point function. They are classified into two types, *viz.* intensive properties and extensive properties. If the value of the property is independent of the mass of the system, it is an intensive property. It is qualitative in nature. Ex: pressure, temperature, density, velocity, height, viscosity, specific property. The pressure is defined as the force exerted normal to a unit area of the boundary. From the continuum point of view, the pressure at a point is the force per unit area in the limit, where area tends to be very small, *i.e.*, approaches to zero.

Pressure as a result of depth of fluid = ρgh

$$P = \frac{w}{A} = \frac{\rho Vg}{A} = \rho gh \tag{1}$$

Atmospheric pressure is the pressure exerted by the weight of the atmospheric air.

P_{atm} = 760 mm of Hg = 101.325 kN/m^2 = 1.01325 bar =1.01325 × 10^5 Pa = 0.101 MPa = 1.113 kg f/cm^2.

The gauge pressure is measured by the instrument (gauge) such as Bourdon, and the manometer is called the gauge pressure.

The absolute pressure measured from the absolute zero pressure is called absolute pressure. Absolute zero occurs when the molecular momentum of fluid is zero. It happens with the perfect vacuum. If the pressure of fluid is less than the atmospheric pressure, it is known as vacuum, rarefaction, or negative pressure. The pressure measured by the instrument does not consider the velocity of the fluid. The gauge pressure is the static pressure. Pressure due to velocity of fluid = $\rho c^2/2$, N/M^2 . The kinetic head expressed in force per unit area is called dynamic pressure. $KE = 1/2\ mc^2$, *j(or Nm)* and therefore:

$$Kinetic\ \ pressure = \frac{1}{2}\frac{mc^2}{V} = \frac{\rho c^2}{2},\ \ N/m^2 \tag{2}$$

Total or stagnation pressure is the sum of static pressure and dynamic pressure. The average density of a system is the ratio of its total mass to its total volume. If the value of the property depends upon the mass of the system, it is known as an extensive property. It is a quantitative property. Ex: volume, surface area, internal energy, P.E. and K.E.

There are five basic or primary thermodynamic properties *viz.* temperature, pressure, volume, entropy, and internal energy. Temperature is a thermal potential and measure of relative hotness or coldness of a system. Pressure is a mechanical potential, normal force per unit area. Volume is the mechanical displacement and the quantity of space possessed by a system. Entropy is the thermal displacement and the quantity of disorder possessed by a system. The kinetic and potential energies of its constituents (atoms and molecules, usually) is the internal energy

CHAPTER 4

Organic Rankine Cycle

Abstract: Basic organic Rankine cycle (ORC) consists of vapor generator (boiler), turbine, condenser and pump. The vapor is generated from the waste heat recovery which is also called as heat recovery vapor generator (HRVG) But due to possibility of internal heat recovery, additionally a regenerator is used between turbine and condenser for internal heat transfer. This chapter highlights the advantage of regenerator over the basic ORC. The performance characteristics of ORC with R123, R124, 134a, R245fa, R717 and R407C are developed. The correlation equations are developed to find the optimum boiler pressure for ORC. The performance has been analyzed with a source temperature below and above the critical temperature of the fluid. The performance characteristics and specifications of ORC with these working fluids are compared.

Keywords: Low temperature heat source, Organic rankine cycle, Regenerator, Thermal power cycle, Working fluid.

INTRODUCTION

A fluid containing carbon based compounds is called as organic fluid. The Organic Rankine Cycle (ORC) uses a fluid with high molecular weight and low boiling point. Organic fluid undergoes chemical deterioration at high temperatures. Therefore, ORC are limited to the low temperature heat sources. The heat rejection from the process industries such as cement factory, steel plant, sponge iron, power plant, kitchen *etc.* is at different temperature levels. In this chapter, low temperature waste heat is used to convert into electricity. The power plant layouts and working fluids are studied. The heat source temperature is changed from 70 °C to 250 °C with the working fluid. The power plant configurations for low temperature heat recovery are ORC, organic flash cycle (OFC) and Kalina cycle (KC). This chapter deals the ORC, its configurations, solutions and performance characteristics. Some working fluids are not suitable to entire range of the temperature. Therefore, from the literature, six working fluids are selected for ORC to study the quantity and quality conversion of waste heat into electricity. Five fluids are single fluids and one is zeotropic mixture. The single fluids are R123, R124 R134a, R245fa and R717. The zeotropic mixture is R407C with fixed concentration. MATLAB computational tool is used for

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properties development, modeling, processes making, cycle simulation and optimization. The energy balance and exergy balance results are depicted on Sankey diagram and Grassmann diagram respectively. The role of components in cycle is analyzed to operate the plant components for maximum energy conversion. Thermodynamic properties at the optimized conditions are presented on property charts and tables. The plant specifications are developed at these conditions.

ORGANIC RANKINE CYCLE WITH SOURCE TEMPERATURE BELOW THE CRITICAL TEMPERATURE

Fig. (**1**) shows the power plant layout of a basic ORC. The fluid expands in turbine from state 1 to state 2 and followed by a condensation (2-3). The saturated liquid at state 3 is pumped to HRVG pressure by feed pump (3-4). The pumped fluid (4) is supplied first to economizer (4-5) where sensible heat of the working fluid gains. Later in evaporator (5-6), the latent heat is supplied by the hot gas. Finally, the fluid is superheated (6-1) by hot gas in HRVG. The hot gas temperature is dropped in superheater (10-11), evaporator (11-12) and economizer (12-13) with counter flow arrangement of hot fluid and cold fluid. The condenser is water cooled heat exchanger with circulating water (14-15) as a heat transfer fluid. The hot water from the condenser is cooled in the cooling tower (not shown) for recirculation from cooling tower to condenser. Alternatively, air cooled condenser also can be used in small size plants and water scarcity areas.

In steam Rankine cycle (SRC), the steam condition at the exit of turbine is in wet state and close to the sink temperature. Therefore, the steam is condensed immediately after the turbine in condenser. Fig. (**2**) shows the temperature-specific entropy plot for the simple ORC. It shows that the exit vapor from the ORC turbine is in superheated state. The exhaust vapor from the turbine is above the saturated temperature. It is to be cooled to condenser temperature and so the condenser load is more with additional sensible heat of in de-superheater. Another side, the condensate needs heating in economizer of HRVG after the pumping. A heat exchanger between these two fluids saves the condenser load and economizer load. Therefore, an internal heat recovery is arranged to transfer the heat from the exhaust vapour to condensate. This heat exchanger is called as regenerator.

Fig. (**3**) shows the ORC with regenerator. Regenerator is a heat exchanger with a hot fluid and cold fluid are vapor and liquid respectively. The vapor temperature is decreasing from state 2 to state 3 with a cold fluid temperature rise from state 5 to state 6. The capacity of condenser and economizer drops with the association of regenerator in ORC. Regenerator influence on HRSG and thermal efficiency but not on power production. The regenerator shares the economizer's load. It improves the thermal efficiency of the cycle by decreasing heat supply.

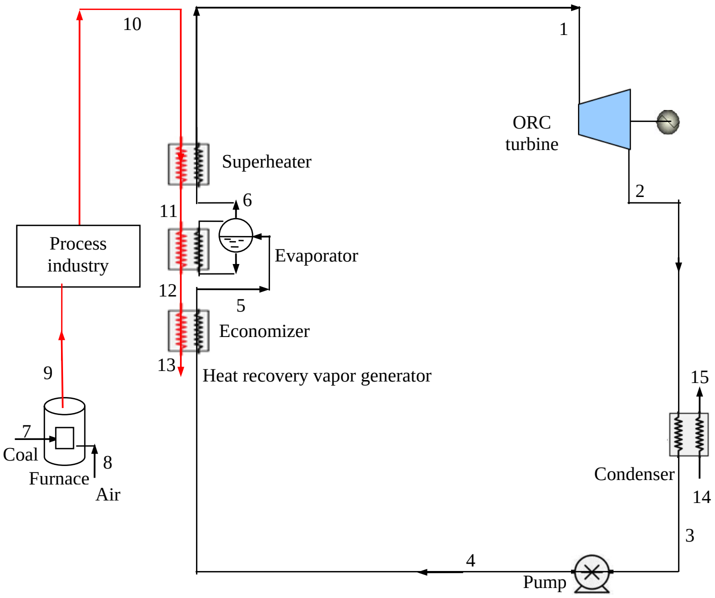

Fig. (1). Basic organic Rankine cycle without regenerator.

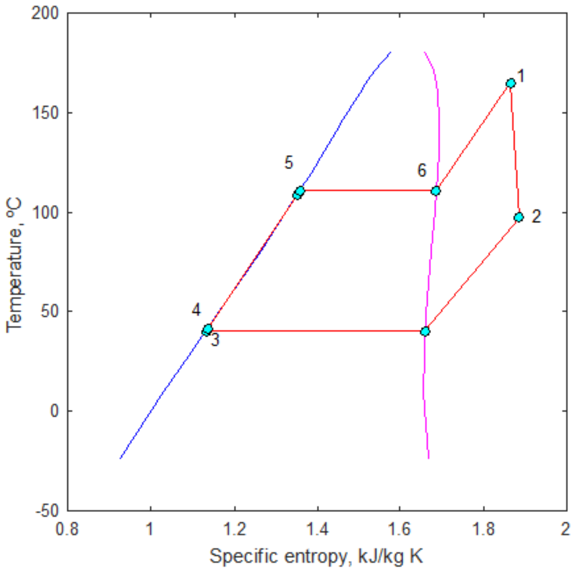

Fig. (2). Temperature-entropy diagram of a basic ORC without regenerator.

CHAPTER 5

Organic Flash Cycle

Abstract: In organic flash cycle (OFC), a small amount of liquid is flashed to a low pressure at the exit of the economizer. The resulted vapour from the flasher is used in turbine for power augmentation. It increases the economizer's load hence a loss in thermal efficiency. OFC has been recommended to power plant operated by waste heat recovery as the focus is on maximum power. The modeling, simulation, analysis and optimization of OFC process conditions are presented to highlight its merits compared to organic Rankine cycle (ORC). The performance variations are analyzed with the source temperature below and above the critical temperature of the working fluid. The studied working fluids in OFC are R123, R124, R134a, R245fa, R717 and R407C.

Keywords: Optimum pressure, Organic flash cycle, Power augmentation, Waste heat recovery.

INTRODUCTION

Organic flash cycle (OFC) is a modified cycle of organic Rankine cycle (ORC) with added flashing unit(s). OFC may have a single flasher or multi flashers. The main goal of the OFC is power augmentation without bothering about the penalty on efficiency. OFC demands more heat addition to the cycle at the same source temperature and fluid compared to ORC. A partial liquid is bled from an economizer in a heat recovery vapour generator (HRVG) and flashed to liquid and vapour. The vapour is separated after flashing and supplied to turbine at the appropriate pressure. The balanced liquid from the separator is recycled to the boiler. The extra vapour supplied to the turbine generated more power and meets the objective of heat recovery. The excess heat addition to economizer with flash option decreases the efficiency. Therefore, OFC is recommended only to waste heat recovery units. A power plant with fuel burning in a furnace demand maximum thermal efficiency to save the fuel. In this chapter, more focus has been given to the double flash power plant due to its potential over the single flash plant. The location of low pressure flasher (LPF) and high pressure flasher (HPF) in a double flash plant has been optimized. The source and sink conditions are also examined to maximize the power.

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ORGANIC FLASH CYCLE WITH SOURCE TEMPERATURE BELOW THE CRITICAL TEMPERATURE

As per the available heat source, the turbine inlet temperature may fall below or above the critical temperature of the fluid. The performance characteristics differs in these regions of temperature. The flash cycle in the current study is different compared to the flash cycle used in a geothermal power plant. The schematic flow diagram of conventional flash cycle is shown in Fig. (**1**) to understand the difference between the current plant and conventional plant. In conventional plant, the complete liquid from the source (1) is flashed into liquid-vapor mixture (2) without subjecting evaporation and superheating. The separated vapor (4) after flashing is expanded in turbine. After expansion, the vapor (5) from the turbine and liquid from the separator (3) are mixed and condensed (6-7) in a closed cycle. The condensed fluid (7) is pumped to well for recirculation.

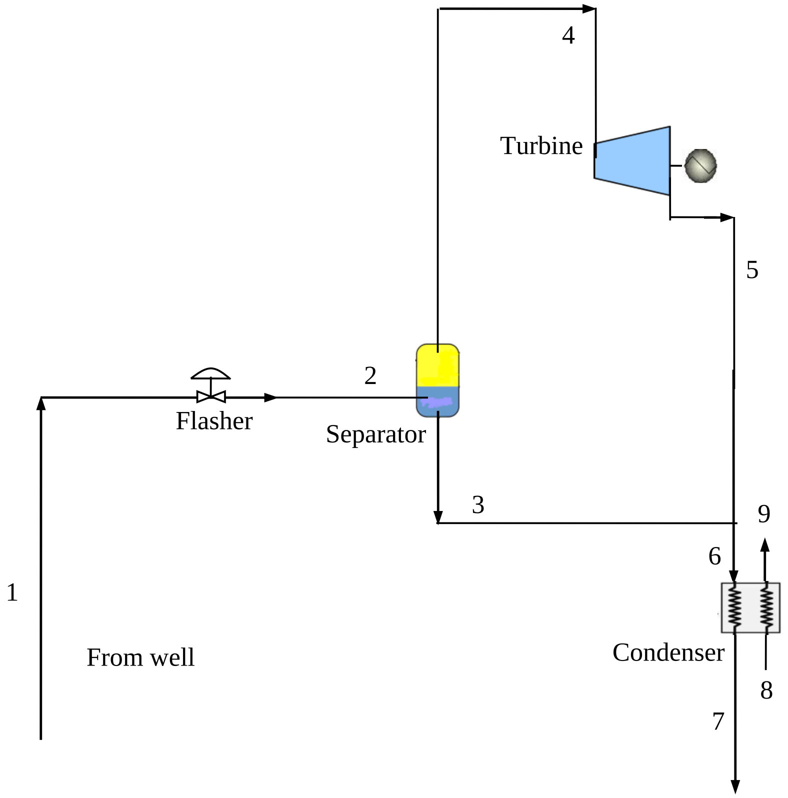

Fig. (1). Flash cycle in a geothermal power plant.

Fig. (**2**) shows the schematic of a single flash cycle suitable for heat recovery and similar energy sources. The vapour temperature at the exit of the turbine allows a regenerator for internal heat recovery and improves the thermal efficiency. So a regenerator is located in OFC similar to ORC. The pumped fluid (14) is flashed in the flasher from high pressure to a low pressure (15) to generate a liquid-vapor mixture. This mixture is separated into liquid (16) and vapor (17) at the exit of the flasher. The vapour is expanded in the turbine (1-4), and the heat has been recovered in the regenerator (4-5). After the internal heat recovery, the vapour is condensed (5-6) to saturated liquid condition (6). The liquid is pumped (6-7) to flasher's pressure (intermediate pressure). The mixed liquid (9) is again pumped (9-10) from the flash pressure to boiler pressure. The temperature of the liquid is increased to the saturation temperature in the economizer (10-11). The fluid is heated from condenser temperature to saturation temperature. From this saturated state, the liquid is divided into flasher (14) and HRVG (12).

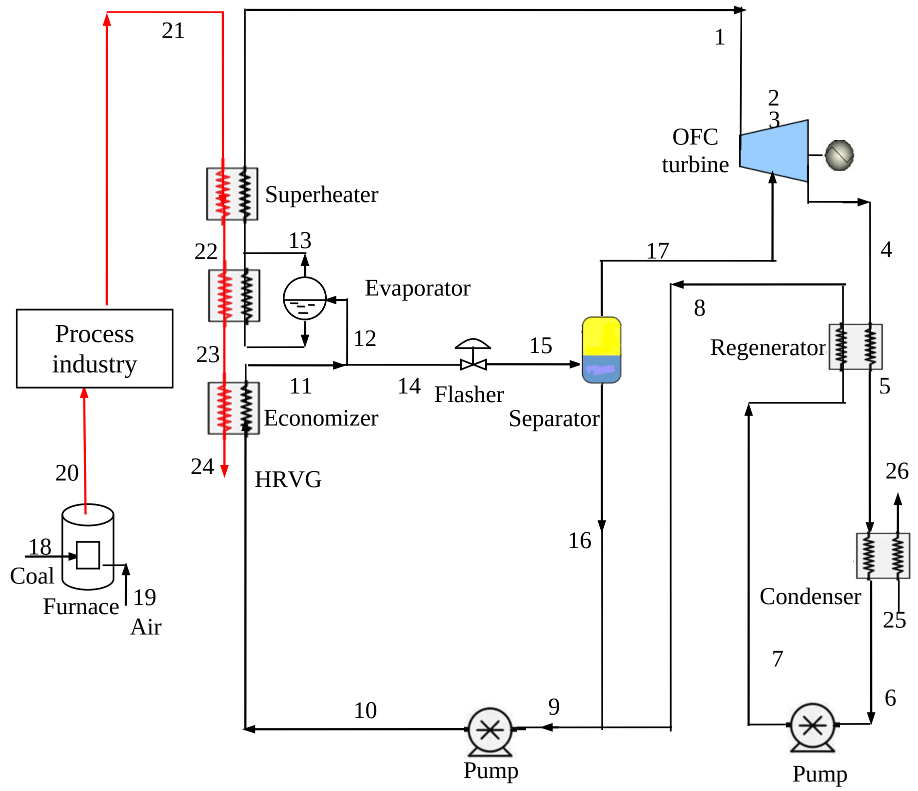

Fig. (2). Organic flash cycle with single flasher.

The liquid in the flasher expands from high pressure to flash pressure through a valve (14-15). It is separated into liquid and vapor. The vapor (17) is supplied to turbine and the balanced liquid (16) is mixed with the condensate. Even through the vapour quantity is low, it enhances the power from the plant. The addition of

CHAPTER 6

Kalina Cycle

Abstract: The plant layout and working of Kalina cycle (KC) differs with the organic Rankine Cycle (ORC), steam Rankine cycle (SRC) and flash cycle. Separation and absorption of binary working fluid makes this cycle a different heat engine cycle. This chapter is aimed at the description, formulation and performance characteristics of KC suitable to a heat recovery. The strong solution concentration and vapour concentration are studied to maximize the power. A suitable KC configuration for the low temperature heat recovery has been selected and studied.

Keywords: Exergy analysis, Heat recovery, Kalina cycle, Modified rankine cycle, Power generation, Thermal efficiency, Thermal power cycles.

INTRODUCTION

Kalina cycle (KC) is a binary vapour absorption power cycle. The heat addition and rejection occurs with the variable temperature. Ammonia-water mixture is used as a working fluid in KC. The addition of ammonia to water permits the operation at low temperature (100 °C – 150 °C). The power plant layout is configured to suit the source temperatures. Water is an ideal fluid in power plant. However, this fluid is not suitable for low temperature heat source. Ammonia cycle is suitable for low temperature heat source. Condensing ammonia in condenser (absorber) is difficult (except at high pressures) as it needs very low temperature (below 0 °C). A feasible condenser can be designed by diluting the ammonia with water. For this process, the plant needs some modifications to the existing Rankine cycle. The process consists of absorption of vapour into the liquid. Therefore, the cycle is called as vapour absorption cycle. The changes in layout need additional components such as separator and mixture. The turbine, condenser (absorber in KC), pump and boiler are the common components in Rankine cycle and KC.

KALINA CYCLE

Fig. (**1**) shows the KC plant layout with industrial waste heat recovery. The cycle consists of external heat recovery, internal heat recovery, machines such as turbine, pump and other heat exchangers *i.e.* absorber, dephlegmator *etc*. The

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external heat recovery in a heat exchanger is called as heat recovery vapour generator (HRVG). The internal heat recovery consists of low temperature regenerator (LTR) and high temperature regenerator (HTR).

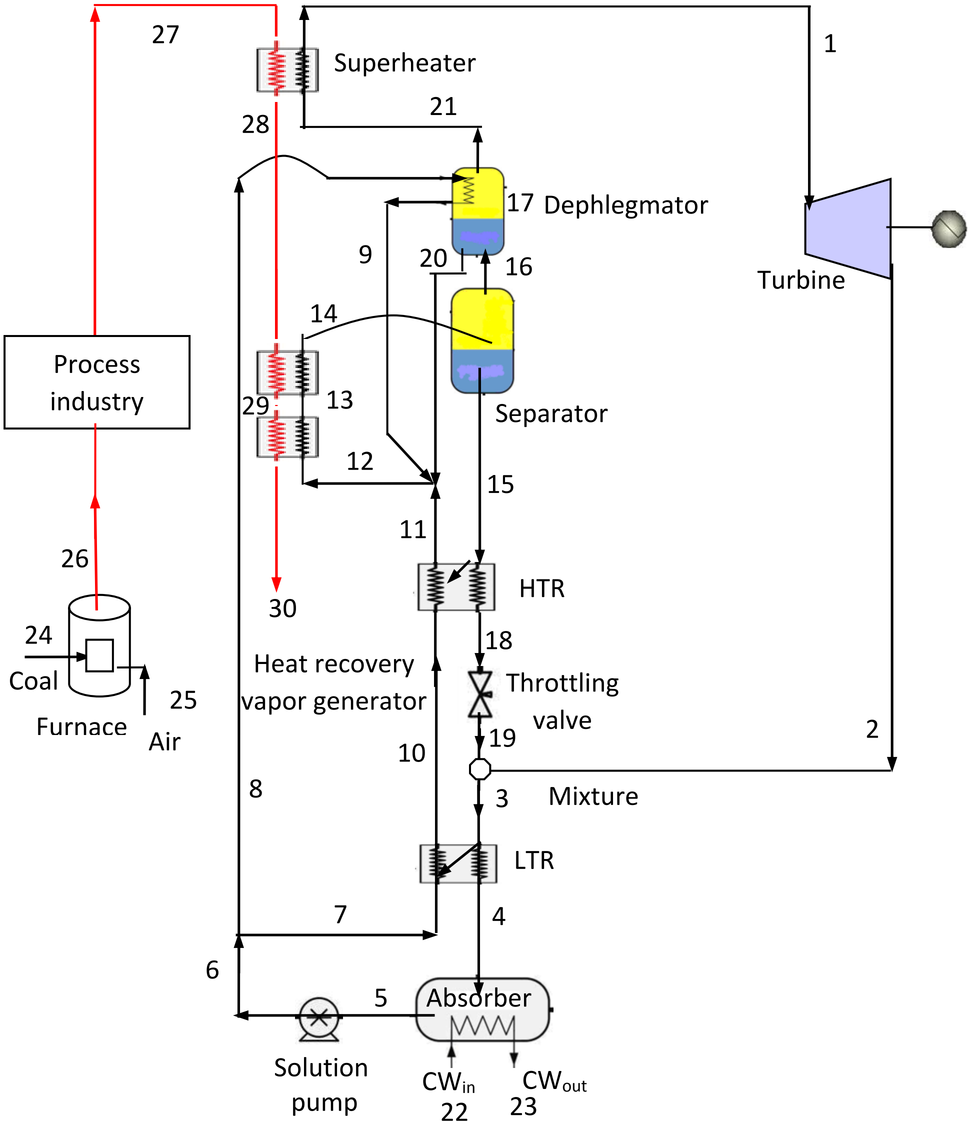

Fig. (1). Power plant layout of Kalina cycle with heat recovery arrangement.

Since the internal heat recovery shares the economizer's load, HRVG has partial section of economizer. The saturated liquid at the inlet of the evaporator is converted into liquid-vapour mixture. The vapour from the separator is superheated and supplied to turbine. The superheated vapour expands in turbine to generate electricity in generator. The condensation of vapour at the exit of turbine is not possible as it demands low temperature sink. Therefore, to condense the vapour at the available sink temperature, the vapour should be diluted by mixing with the weak solution. The weak solution is a separated liquid from the separator. The weak solution after mixing with vapour is capable of internal heat recovery. Therefore, LTR is located between mixture and absorber. The absorber is an air cooled or water cooled condenser to condense the mixture into saturated liquid. The liquid is pumped to HRVG to generate the vapour for the cycle. HRVG converts the preheated liquid from LTR and HTR into a liquid-vapour mixture. The turbine demands vapour without any liquid traces. Therefore, the vapour and liquid are separated after HRVG. The vapour is supplied to dephlegmator and weak solution is passed through internal heat recovery and throttling. Dephlegmator is a heat and mass transfer unit located between separator and superheater. The dephlagmator increases the concentration of vapour by condensing the water from the vapour. The incorporation of dephlegmator permits the engineer to design the plant at the low pressure.

(Fig. **2**) shows pressure-enthalpy diagram of KC with all the processes. The concentration curves are shown for liquid side (left side) and vapour side (right side). The high pressure and low pressure are the two horizontal lines. The expansion of vapour has been depicted with a drop in pressure and temperature. The mixing before absorber is a horizontal line. Similarly, the mixing of fluids at the inlet of HRVG is a horizontal line. The throttling from high pressure to low pressure and pumping from low pressure to high pressure are shown as vertical lines.

Table **1** lists the thermal properties of KC shown in (Fig. **1**). The two pressures in the cycle are high pressure (13.78 bar) and low pressure (2.58 bar). The combustion and process states are shown from state 25 to state 27. The hot gas temperature is dropped from state 27 to state 30. The strong solution concentration is 0.4. The weak solution concentration is 0.26. The vapour concentration at the exit of separator is 0.85. The concentration is increased from 0.85 to 0.87 in the dephlegmator. As per the assumptions, at the hot gas supply temperature of 150 °C, the resulted turbine inlet temperature is 135 °C.

Table 1. KC material balance results.

State	P, bar	t, °C	x	m, kg/s	h, kJ/kg	s, kJ/kg K
1	13.78	135.00	0.87	7.62	1689.12	5.29
2	2.58	65.60	0.87	7.62	1449.59	5.40
3	2.58	66.28	0.40	32.96	484.22	2.11

CHAPTER 7

Steam Rankine Cycle

Abstract: Steam Rankine cycle (SRC) is a widely used thermal power cycle due to its ideal properties of the fluid. Compared to organic Rankine cycle (ORC) and organic flash cycle (OFC), the working fluid and equipment are not expensive. A water treatment plant is associated with a steam thermal power plant. SRC is a power plant cycle in thermal power plant, bottoming cycle in a combined cycle power plant or power generation cycle for a waste heat recovery plant. In this chapter, the performance characteristics of SRC have been developed and analyzed. A single pressure heat recovery steam generator (HRSG) with a deaerator is considered to draw the heat from the industrial waste heat. The conditions for maximum power and maximum efficiency have been developed. Correlations are presented to find the HRSG pressure at the available hot gas supply temperature. The work is extended to a case study on SRC operating with the heat recovery of a cement factory. A power plant layout suitable to the identified waste heat sources from a cement factory has been developed. From the evaluation, it has been concluded that approximately 15 MW of electricity can be generated from its waste heat to meet the electrical load of 15 MW. It indicates that at the optimized conditions, it is possible to self-generate the electrical demand of the cement factory from its own waste heat recovery. The analysis recommended a low pressure in HRSG for maximum power generation.

Keywords: Heat recovery, Rankine cycle, Steam power cycle, Thermal efficiency, Thermal power plant.

INTRODUCTION

In majority of countries, more than 50% of electricity is from thermal power plant with steam as a working fluid. The power cycle is a steam Rankine cycle (SRC). Water is the ideal fluid for power. To operate SRC, a water treatment plant is required. The thermal properties of water/steam are superior than the others. Large size power plants can be suitably built with water as the working fluid. The equipment and systems are well developed and available around the world. The main challenges of thermal power plants are the handling of dust, ash and environmental pollution caused by the burning of coal. The ash and emission issues can be addressed by shifting from coal firing to heat recovery option or biomass firing. SRC is not suitable for a power plant with low temperature heat source. Organic Rankine cycle (ORC) is similar to SRC layout.

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ORC is suitable for low temperature heat sources. The SRC is suitable for the source above this temperature and up to 600 °C with the limitation in material properties. Above this temperature, erosion of steam turbine occurs. SRC can be operated by fuel firing, solar thermal collectors and waste heat recovery. In this chapter, waste heat has been selected. Majority of components in the basic layout of SRC and ORC are same, except for a few changes. The vapor temperature at the exit of turbine differs in SRC and ORC. In SRC, it is close to sink temperature, except back pressure turbine. In back pressure turbine steam expands to 100 °C for space heating or any process heat. The turbine exit in ORC is above the sink temperature. Therefore, at the exit of ORC turbine, regenerator is used and it is not possible in SRC. The focus of this chapter is the study and analysis of SRC.

STEAM RANKINE CYCLE

Fig. (**1**) shows the thermal power cycle of SRC with a deaerator. In a furnace, coal is fired to generate heat for process industry (here cement factory) and power plant. Fig. (**2**) shows the temperature-entropy diagram of the SRC. The hot gas is supplied to the cement processing and later to power plant. SRC shown in Fig. (**1**) consists of heat recovery steam generator (HRSG), turbine, water cooled condenser, two pumps and a deaerator. Steam is generated in the HRSG from the heat of hot gas supplied from the factory. The superheated steam is expanded in turbine and condensed to saturated water. The cycle has three pressures *viz.* HRSG pressure, deaerator pressure and condenser pressure. After the condenser, the water is pumped from the condenser pressure to deaerator pressure. In the deaerator, the steam from the turbine and pumped water mix with each other and turned into saturated liquid. Deaerator is an open feedwater heater used to remove the dissolved gases from working fluid (deaeration) and increase the feedwater temperature.

The dissolved gases in water causes corrosion of the boiler parts. They also reduce the heat transfer capacity between hot fluid and cold fluid. For example, oxygen presented in water creates pitting at the local regions of heat exchanger. Water with ammonia corrodes the copper based material in the heat recovery and bearings. The vacuum pressure in deaerator can be used in the power plant system. Vacuum ejectors are used in the vacuum deaeration. To remove the dissolved gases from the deaerator, a vacuum pump is used in vacuum deaeration. However, the deaerator pressure above the atmospheric pressure is most commonly used method in the power plant. In closed feedwater heater, heat transfers from steam to feed water without mixing. The preheating of water before HRSG in a deaerator increases the thermal efficiency with a drop in turbine output. The feedwater is pumped from the deaerator pressure to HRSG pressure.

HRSG consists of economizer, evaporator and superheater. This cycle repeats on steady state for continuous power generation.

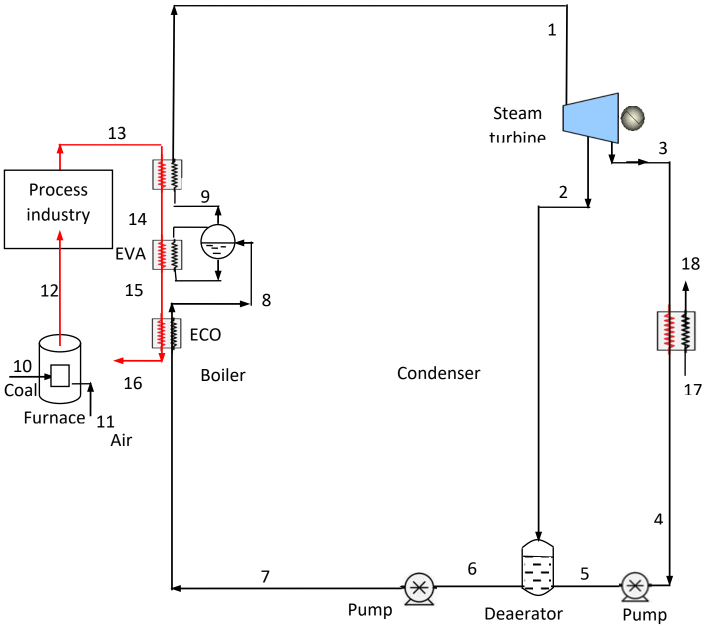

Fig. (1). Schematic plant layout of SRC with a deaerator.

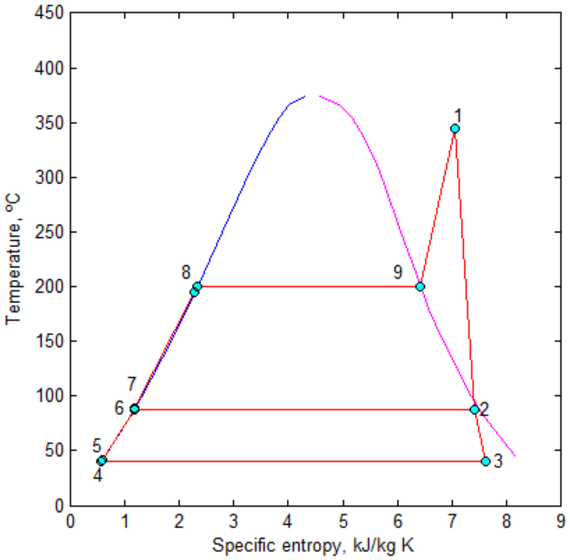

Fig. (2). Temperature-entropy diagram for SRC with a deaerator.

CHAPTER 8

Steam Flash Cycle

Abstract: Similar to the organic flash cycle (OFC), steam flash cycle (SFC) consists of flasher to expand the liquid into liquid-vapour mixture from high pressure to low pressure. It has a significant role in power augmentation through heat recovery. This chapter reports the formulation, analysis, and performance characteristics of SFC. The performance changes of OFC with single flash and double flash are studied and compared. The source temperature is changed below and above the critical temperature of the water. Correlations are developed to find the optimum heat recovery steam generator's (HRSG's) pressure as a function of source temperature. The location of a single flash and double flash units are optimized at maximum power condition. The work is extended to generalize the SFC formulation to solve with 'n' number of flashers to simplify the complex formulae. This generalization can be used to optimize the number of flashers. A case study on SFC has been presented to understand the power generation processes with heat recovery.

Keywords: Optimum boiler pressure, Power augmentation, Steam flash, Thermal efficiency, Thermal power plant.

INTRODUCTION

Use of heat recovery in place of fuel firing in a thermal power plant has benefits *viz.* fuel-free, economic, no emissions, and no ash and dust. The industry wasting thermal energy can use it and generate its own electricity demand without depending on the grid. These power plants are also suitable for decentralized power generation to meet the load of small colonies, villages, *etc.* This chapter is focused on the steam flash cycle (SFC) for augmented power compared to the conventional steam Rankine cycle (SRC). The waste heat from a typical cement factory is considered as a heat source to the SFC. The study of the cement factory is not the scope of the current chapter. This chapter is focused on the power generation unit to maximize heat recovery and power. In the combustion chamber, fuel (coal) and air are supplied to generate heat used for cement production, and the rest of the waste heat is supplied to the steam-generating unit. Since steam is generated in the boiler from heat recovery, the boiler is known as a heat recovery steam generator (HRSG). In a regular steam power plant with a deaerator, steam has been generated at single pressure in three units *i.e.* economizer (ECO), evaporator (EVA) and superheater (SH). The local hot gas temperatures are

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determined using pinch point (PP) and terminal temperature difference (TTD). The condensed steam is pumped to deaerator and boiler using two pumps. In SRC, steam is consumed for feedwater heater and it drops the power production.

Flashing of pressurized hot water differ from geothermal power plant's flasher to OFC. In geothermal plant, total fluid undergoes flashing process. But in SFC, a small amount of pressurized water from the economizer of heat recovery steam generator (HRSG) is used in a flasher. The balanced fluid undergoes the regular SRC processes. SFC combines the features of SRC and flash cycle. The heat load in economizer increases compared to SRC due to the handling of excess fluid. Therefore, thermal efficiency increases with an increase in heat supply. Since the main objective of the heat recovery is to maximize power generation, the drop in efficiency is not the issue in the flash cycle. After flashing, the separated liquid goes to the boiler and the vapour expands in the turbine. The added vapour in the turbine increases the power with a penalty in efficiency. The process in a regenerative steam Rankine cycle is reversed compared to a flash cycle. In a feedwater heating system, steam from the turbine is used to preheat the water to save the heat supply to the plant. So, feedwater heating system supports the thermal efficiency but cuts the power from the turbine. In SFC, flasher supports the power but not the efficiency. In the multi flashing plant, the balanced liquid from the first flasher is supplied to the subsequent flasher. The increased economizer load drops the exhaust gas temperature. The work is focused on thermodynamic development, optimization of boiler pressure with source temperature, performance characteristics, generalization of SFC, and case study on SFC.

STEAM FLASH CYCLE

Fig. (**1**) shows the plant layout of SFC with a single flasher. The concerned thermodynamic cycle has been depicted in Fig. (**2**) . In addition to the components used in a basic Rankine cycle, flasher with separator is used as an extra component. The flash cycle works on three pressures *viz.*, HRSG pressure, flash pressure, and condenser pressure with the flasher. The superheated steam expands from the high pressure to flash pressure. At the exit of first stage expansion, the vapour is mixed with the separated vapour from the flasher unit. The mixed vapour is then expanded from the flash pressure to condenser pressure. The expanded steam as usual condensed in the condenser as shown in water cooled condenser. The condensate is pumped from condenser (low) pressure to flash pressure. At this intermediate pressure, the pumped fluid and liquid part from the flashing unit are mixed and followed by pumping from flash pressure to HRSG (high) pressure. The pressurized water is supplied to the economizer section of HRSG. In the HRSG the temperature of water is reached closed to saturation temperature corresponding to HRSG pressure. This is below the saturation point by the approach point (AP). The heat recovery consists of hot gas from the industry, such as a typical cement factory. The hot gas temperature is decreased in superheater, evaporator and economizer with a constraint of pinch point (PP).

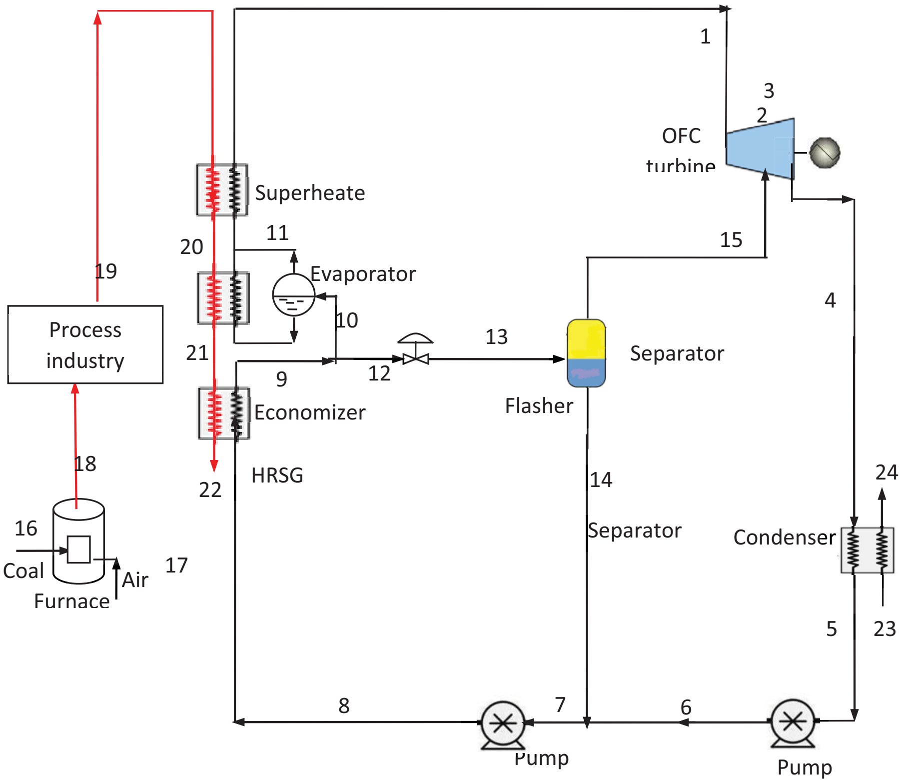

Fig. (1). SFC with single flasher.

The hot gas solution and its formulation are furnished in the earlier chapters. In the single flash SFC, the performance has been evaluated from the mass and energy formulation. For this assumptions made are as follows:

The hot gas flow rate is 1000000 m^3/h. The combustion temperature is 900 °C. The temperature of circulating water in the condenser is 30 °C. The mechanical efficiency of pump and turbine is 98%. Similarly, the electrical efficiency of generator is 98%. The isentropic efficiency of pump and turbine are 75% and 80% respectively. Approach point is 5 °C. Terminal temperature difference (TTD) in condenser is 10 °C. Initially, the power cycle has been solved with unit mass flow at the turbine inlet. Later, steam generation is evaluated from the energy balance of evaporator and economizer sections.

CHAPTER 9

Comparison of Thermal Power Cycles

Abstract: This chapter summarizes the book by the comparison of all the thermal power cycles under a common platform. Some outcomes of the book have been drawn through this comparative analysis. All the thermal cycles of heat recovery power plants are consolidated in this comparative analysis. The organic Rankine cycle (ORC), organic flash cycle (OFC), steam Rankine cycle (SRC) and steam flash cycle (SFC) are compared and analyzed below and above the critical temperature of working fluid. The six working fluids used in ORC and OFC are R123, R124, R134a, R245fa, R717 and R407C. The performance of Kalina cycle (KC) is also added to differentiate with the ORC and OFC characteristics. R123 in OFC has been recommended to result in higher power compared to the other fluids. After the low temperature cycles (ORC, OFC and KC), the next level of source temperature has been analyzed with steam power cycles (SRC and SFC). The SRC, SFC with one flasher (SFC 1), and SFC with two flashers (SFC 2) are compared for the power and efficiency variations with a change in temperature and pressure. From the steam cycles, SFC 2 has been recommended to waste heat transfer for power augmentation. The analysis shows that the R134a and R245fa are not able to augment the power with OFC plant. OFC- R407C is only escalating the thermal efficiency in addition to the power augmentation due to the use of zeotropic working fluid. R717 exhibits maximum specific power with ORC and OFC with higher optimized heat recovery pressure.

Keywords: Comparative analysis, Energy efficiency, Power augmentation, Thermal power plants, Waste heat recovery.

INTRODUCTION

In the earlier chapters, the individual power plant cycles are detailed *viz.* organic Rankine cycle (ORC), organic flash cycle (OFC), Kalina cycle (KC), steam Rankine cycle (SRC) and steam flash cycle (SFC). The studied working fluids in ORC and OFC are R123, R124, R134a, R245fa, R717 and R407C. Out of these working fluids, R407C is the zeotropic mixture. KC also works with zeotropic mixture but the cycle undergoes binary fluid processes such as absorption and separation. Zeotropic mixture has an advantage of glide in boiling and condensation. This glide helps to match the temperature profile of heat source. Two types of steam cycles are selected in the thermal power cycle *viz.*, SRC and SFC. The main focus of this chapter is the comparative analysis of all these thermal power cycles to make some useful recommendations.

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COMPARISON OF ORC, OFC, AND KC

Each chapter in this book is focused on a thermal cycle of heat recovery power plant. Performance of each thermal cycle has been studied with the selected working fluids. The recommendations in the earlier chapters are made from the comparison of same category of layout with a change in working fluid. This chapter compares all the categories under common ground. A wider outcome can be expected from this overall comparison. Figs. (**1** - **6**) compares the ORC and OFC with the six working fluids for power and efficiency changes.

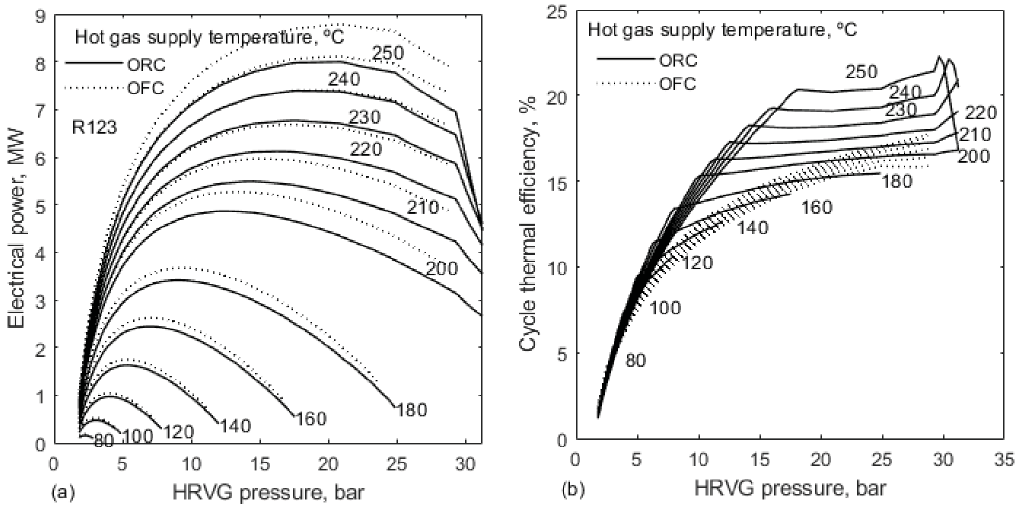

Fig. (1). Comparison of **(a)** power and **(b)** thermal efficiency of ORC and OFC with source temperature below and above the critical temperature of R123.

Figs. (**1a** and **1b**) shows the power and thermal efficiency characteristics developed for ORC and OFC with R123. The augmentation in power with OFC increases with increase in source temperature. The performance characteristics below and above the critical temperature are plotted. A greater improvement in power has been observed from the source temperature, below the critical temperature to above the critical temperature of the fluid. This Figure also shows that the optimum pressure increases with an increase in the source temperature. Thermal efficiency increases with an increase in source temperature at a diminishing rate. The increase in source temperature increases the optimum HRVG pressure. It limits the vapor generation with a limit in the pinch point. Therefore, the efficiency increases at a diminishing rate with a rise in the temperature.

Fig. (**2**) outlines the performance characteristics of R124. A favorable power augmentation is observed with OFC. In the majority of cases, the optimum OFC pressure is more than the optimum ORC pressure. R717 shows a lower OFC pressure compared to ORC pressure. It is due to the higher pump supply with high HRVG pressure. The power and thermal efficiency decrease with OFC-R134a. The deviation between ORC and OFC characteristics is more with R134a. A similar deviation in power and efficiency has been observed with R245fa (Fig. **4**).

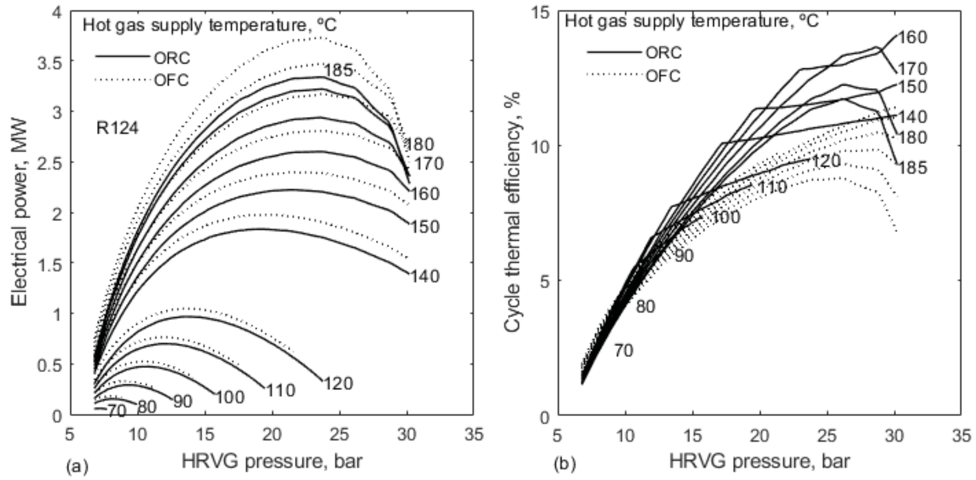

Fig. (2). Comparison of **(a)** power and **(b)** thermal efficiency of ORC and OFC with source temperature below and above the critical temperature of R124.

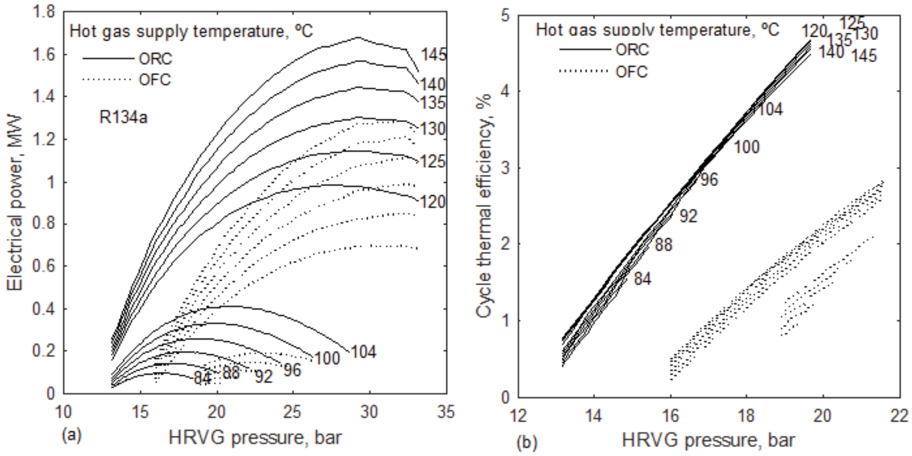

Fig. (3). Comparison of **(a)** power and **(b)** thermal efficiency of ORC and OFC with source temperature below and above the critical temperature of R134a.

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