ORC – ORGANIC RANKINE CYCLE ALSO IN SLOVENIA

Andrej SENEGAČNIK, Uroš GLAVINA, Mihael SEKAVČNIK

ABSTRACT

The article deals with ORC (Organic Rankine Cycle) process. This is a thermodynamic power cycle for conversion low temperature heat into mechanical work. The working media is an organic refrigerant. Operating parameters are lower than in water cycle. Due to specific properties of refrigerant also the ORC process has some peculiarities. The article presents the ORC process, which is applied in the Slovenian industry. Generator power is 125 kW, working media is HFC245 fa (R245 fa). Some specific features and operating experience of ORC processes are addressed in this article.

POVZETEK

Članek obravnava ORC (Organic Rankine Cycle) proces. To je delovni krožni proces namenjen pretvorbi nizko temperaturne toplote v mehansko delo – električno energijo. Delovna snov je organsko hladivo, ki se uparja pri nižjih parametrih kot voda. Zaradi spremenjenih lastnosti hladiva, glede na vodo ima tudi ORC proces nekatere posebnosti. V članku je predstavljen ORC proces, ki je apliciran v slovenski industriji. Električna moč generatorja je 125 kW, delovna snov je HFC245 fa (R245 fa). Prikazane so nekatere posebnosti in dosedanje obratovalne izkušnje z ORC procesom

1. INTRODUCTION

Due to the increasing demand for reduction of environmental pollution on a global scale and to reduce global warming with the greenhouse effect of fossil fuel use one searches various niches of heat sources to produce mechanical work – electricity. Important but so far ignored sources of heat are waste heat flows from industry processes. These energy sources are usually low (t < 300 °C) and medium temperature (t < 500 °C) flue gases and sometimes also low-pressure water steam. Nowadays also exhaust gases from the stabile Otto engines located at dumps and biogas plants appear as a high temperature (t > 500 °C) heat source.

Sadi Carnot in 1824 discovered one of the fundamental natural laws of limited conversion of heat into mechanical work. Carnot's theorem states that the ratio of mechanical work obtained, the amount of heat input, and also discharged heat (thermal efficiency of the process) is proportional to the temperatures of heat input and heat sink. Ideally, the efficiency is expressed as $\eta_C = 1 - T_{out}/T_{in}$. Real heat engines are optimized in a view of maximum power production rather than maximum efficiency (i.e. minimum fuel consumption at maximum work output). Processes with maximum efficiency would run extremely slow, with small power and the apparatus would be very expensive. Courzon–Ahlborn's theorem states [**Error! Reference source not found.**] that due to unavoidable heat transfer irreversibility (limited heat transfer areas and limited time for the heat transfer) the thermal efficiency additionally drops to $\eta_{CA} = 1-(T_{out}/T_{in})^{1/2}$. At this η_{CA} efficiency the maximum power occurs. This is also valid for ORC processes. Therefore the efficiency of treated ORC process is very close to the η_{CA} efficiency.

If the heat source is low temperature, classic Rankine cycle fails due to inability of water evaporation. Therefore water is no longer suitable as working media. If instead of water an organic fluid is used one gets so-called ORC - Organic Rankine cycle. Some organic working media with appropriate characteristics is used i.e. hydrofluorocarbons, which begin to evaporate at significantly lower parameters (temperature) than the water does. The most suitable organic working media is chosen according to the temperature boundary conditions of waste heat (heat source) and environment (heat sink) [8].

2. ORC PROCESS IN SLOVENIA

ORC deployment project provides the repowering of low temperature waste heat at several locations in the Slovenian industry [**Error! Reference source not found.**]. Launch of the first ORC plant was made in the second half of the year 2010. The basic condition, which the certain location must meet, is sufficiently large heat flow of waste heat ~1 MW, the corresponding temperatures and the possibility of heat extraction from ORC process into the environment. Several possible locations which meet those basic technological requirements have been investigated for this reason. There are not many relevant sites in the Slovenian industry because we do not have any large industry facilities. A requirement for about 1 MW of waste heat arises from the fact that the provider of the basic unit of ORC process comes from the USA (company GE Power&Water, Heat Recovery Solutions), where the number of appropriate "large" sites is significantly higher.

2.1 Basic description of the ORC process

Schematically the ORC process and the corresponding *T-s* diagram are shown in Figures 1 and 2, respectively. The Figures show the situation where the heat input of the ORC process is supplied with superheated steam. Heat input consists of four different thermodynamic processes (heating, evaporation, superheating,...), this is schematically presented with different elements. In Figure 1, the central part of the ORC is marked which is imported from the USA as a whole. For establishing ORC at the given location two heat exchangers – for heat input (evaporator) and heat extraction (condenser) should be designed according to the available parameters of the heat source and heat sink into the environment [**Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**].

The basic characteristics of ORC process, which is applied in Slovenia are:

- ORC working media – refrigerant HFC245 fa - 1,1,1,3,3-pentafluoropropane (denotation R245 fa is also used);
- the parameters of fresh superheated steam HFC245 fa at turbine inlet: 20 bar, 125 °C condensation parameters: 2.3 bar, 38 ° C
- mass flow of HFC245 fa: 4.02 kg/s
- electric power of generator: 125 kW
- single case sealed compact turbine and generator with magnetic noncontact bearings, 24000-30000 revolutions per minute
- AC current of variant frequencies from the generator is rectified to DC and than transformed back to grid's AC – 3P, 50 Hz, 0.4 kV. Transformation losses due to twice AC/DC/AC converting are ~8 %

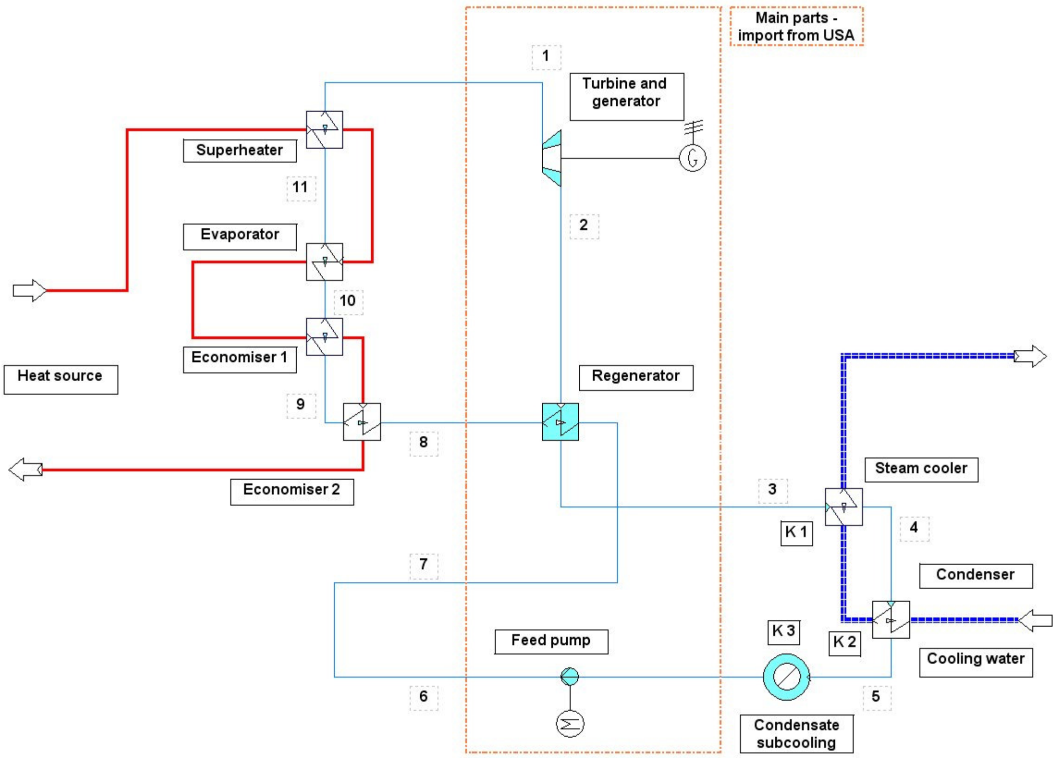

Figure 1: Basic schema of ORC process

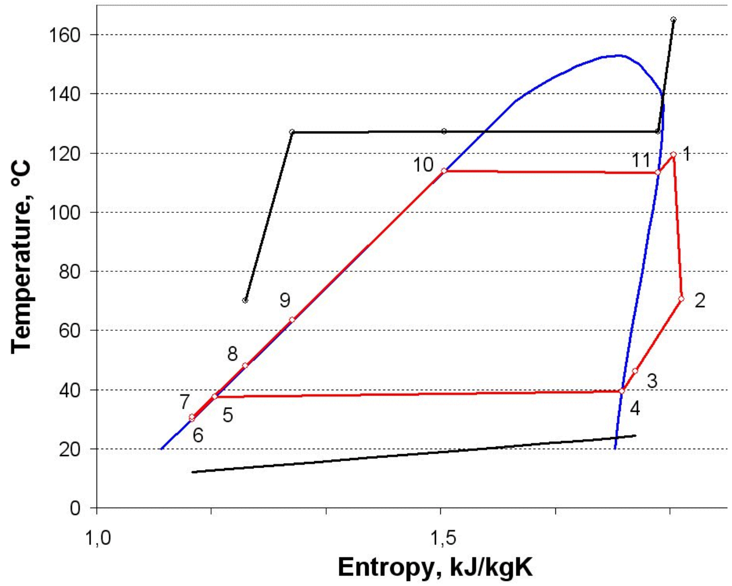

Figure 2: Diagram *T–s* of ORC process

As shown in the diagram *T-s* for the ORC process the working media is characterized by the specific limit curve, resulting in increasingly superheated steam after the expansion in steam turbine. Since the isentropic expansion of steam can not reach the saturation curve the steam has to be cooled down after the expansion. In regenerator superheated steam cools down and the heat is transferred to liquid feeding refrigerant HFC245 fa. So this is classical regenerative heating process, with a difference that the heating medium does not condense like in case of water Rankine cycle. In the diagram *T-s*, Figure 2, the black lines show the temperature characteristics of the heat source and heat sink.

2.2 Thermodynamic parameters of ORC process

Figure 3 shows the energy and mass balance of operating ORC at partial load, generator power 108 kW (full power 125 kW). Superheated steam with pressure of 2.4 bar and temperature 165 °C is used as the heat source. The advisability of the use of water steam to drive the ORC is of course questionable. Due to state financial stimulation/subvention (feed-in tariffs) for electricity generated in CHP (Combined Heat and Power) and RES (renewable energy sources) for ORC plants the use of water steam becomes also profitable. In a case of "green electricity" (wood, biomass, CHP production) the state guarantees energy trade at guaranteed price.

When the refrigerant HFC245 fa is heated, water steam condenses. Thermodynamically, these are four different processes and are therefore considered separately; economizer 1 (water condensate sub-cooling), economizer 2 (HFC245 fa heating to boiling point), evaporator and superheater. It is also similar with the heat extraction, where we first have steam cooler, condenser, and sub-cooling of condensate. The parameters in Figure 3 were obtained during ORC operation in Slovenia. Energy and mass balance is calculated with software package IPSEpro 4.0 [**Error! Reference source not found.**].

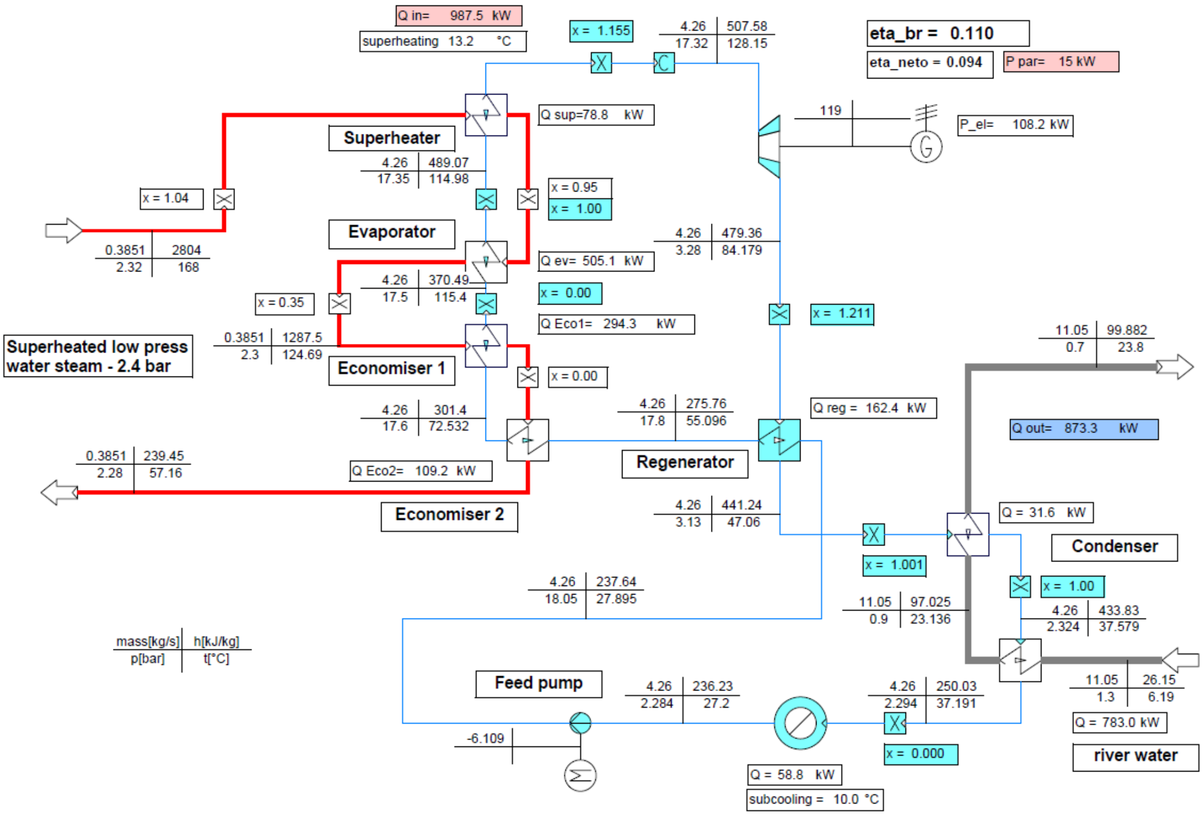

Figure 3: Parameters of ORC plant at generator power of 108 kW

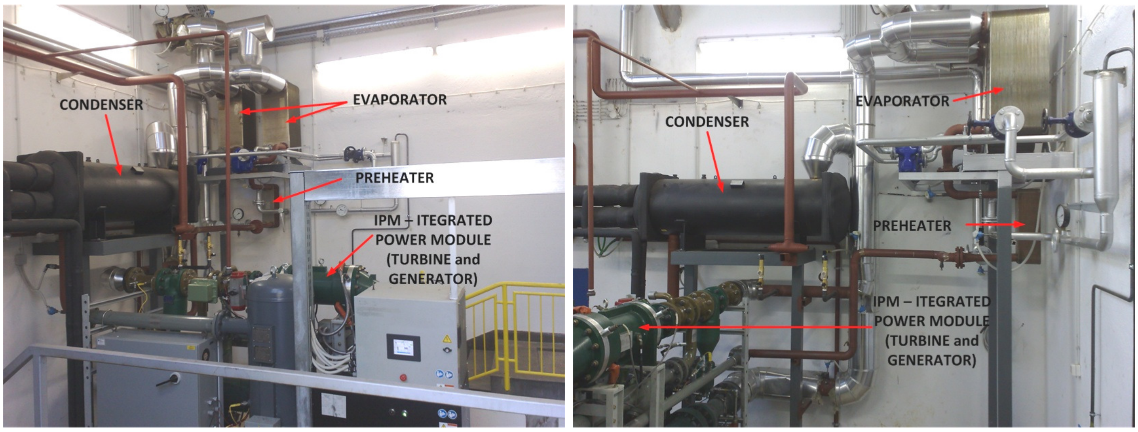

Figure 4: Pilot ORC plant in Slovenia

3. SEALING TECHNOLOGY IN ORC

Employment of refrigerant gas HFC245 fa for working media in ORC process demands to meet the requirements of refrigeration technology regulations. Global warming potential of refrigerant gases is commonly more than 1000 higher than for carbon dioxide. From the

environmental point of view as well as from the operating costs point of view (high taxes and purchase costs for HFC245 fa system refueling) there is a need to ensure minimum leakage.
Measures that enable attainment of minimum leakage:

- Minimizing number of dismantling connections in the system
- Threaded connections with copper gasket or O-ring (pressure and temperature probes…)
- Usage of suitable sealants for connections (Loctite, X-pando etc.)
- NPT (National Pipe Thread Tapered)
- Refrigerant technology flanges (e.g. ammonia flanges)
- Following assembly demands and procedures – clean flange faces, proper gasket, usage of torque wrench, lubrication of bolts with grease, tightening up the flanges with a specified torqueing pattern

4. OPERATING EXPERIENCE

First ORC that is installed in Kamnik area has more than 3200 operating hours (at the time of writing the article). It has transferred over 259 MWh of electricity to grid and generated over 296 MWh of electricity on the generator. Specific parasite power consumption of ORC is thus ~12.5 %. Gross electrical efficiency for discussed operation period is ~11 % and net efficiency (considering ORC parasite power consumption) over 9.6 %. Net efficiency is dependent on environment conditions of ORC location, i.e. heat input and heat extraction. Heat extraction system (condenser) has a large influence on ORC's own power consumption. At the Kamnik ORC, heat is extracted to creek and consequently the power consumption of cooling pump is relatively low. If heat is extracted to environment with air condensers, power consumption could significantly increase due to fan drive to induce force draft (especially on hot summer days).

ORC governing system with sensors, actuators and safety equipment enable highly autonomous operation and consequently reduce operating costs. ORC is in ready-to-start state if there is neither fault state nor any element breakdown. When all start-up conditions are fulfilled, i.e. heat source requirements are reached (sufficient temperature of superheated water steam), ORC starts automatically. With emergency stop fault the installation should be visually inspected and fault manually cleared on the ORC HMI. It is advised to have a diary of leak tests which are performed within a defined time interval (once a month, once on 3 months or similar). Leak tests are performed on all connections with hand leak sensor (advised to be calibrated for HFC245 fa).

Installation costs are highly dependent on environment where ORC is installed. Heat source type (steam, exhaust gases,…) defines ORC heat input system. There are different possibilities to transfer heat into ORC, direct or indirect configuration. First ORC in Kamnik area is a direct configuration, where heat source interacts directly with the HFC245 fa. With the indirect configuration secondary fluid (typically pressurized hot water) is used to transfer heat from heat source to the HFC245 fa (stable gas engines on biogas). Installation environment also defines need for sensors, actuators and safety equipment. With direct configuration most of sensors, actuators and safety equipment is already installed at the heat source system. On the other hand with indirect configuration all these equipment needs to be installed with ORC.

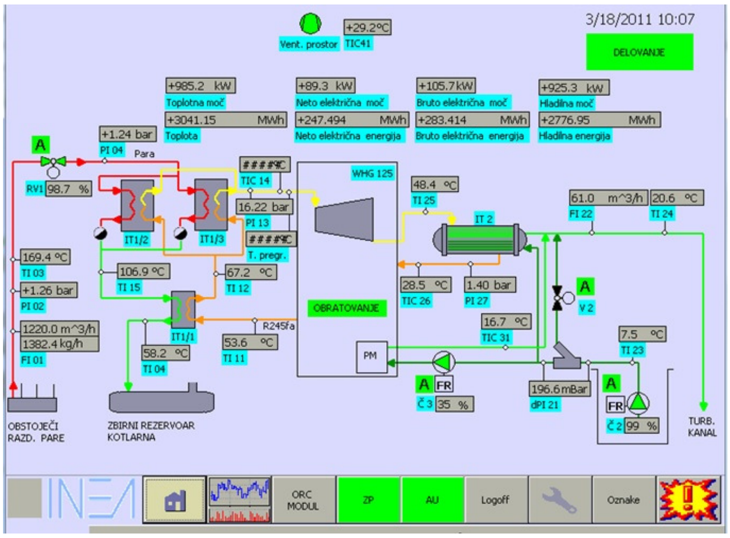

Figure 5: Basic layout of remote access monitoring and control system

Operating and maintenance costs are expected to be low since ORC control, sensors, actuators and safety equipment eliminate need for permanent presence of professional personnel, since ORC control. Integration of magnetic bearings in IPM module (turbine and generator set) eliminated need for lubrication system which effects on simplified operation, maintenance and reduces operation and maintenance costs.

5. CONCLUSIONS

The article deals with ORC (Organic Rankine Cycle) process. This is a heat engine designed to transform low-temperature heat to shaft power / electricity. ORC process is a classical Rankine cycle where an organic working media – various organic coolants are used instead of water. ORC cycle is like Rankine cycle bounded with two isobaric and two isentropic processes. Typical characteristic of organic refrigerants is also a lean saturation curve which makes the steam along the isentropic expansion superheated. The article presents the ORC process applied in the Slovenian industry. Basic characteristics of this ORC process are: organic refrigerant HFC245 fa as working medium, mass flow 4 kg/s, temperature of steam entering the turbine 125 °C, electric power of generator 120 kW, input heat flow 930 kW, net efficiency of the process ~9,6 %. So far ORC plant operated 3200 hours and delivered ~250 MWh of electricity to the grid. Expected operating and maintaining costs are low. System is designed to be controlled remotely with a high degree of autonomy. Therefore the system can operate without any active human control, even at start up or shut down. Modern technology of contactless magnetic bearings for turbine and generator shaft simplifies maintenance / operating and also reduces the operating costs.

6. REFERENCES

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AUTHOR ADDRESSES

Assoc. Prof. Dr. Andrej Senegačnik – Faculty of Mechanical engineering, Ljubljana
Uroš Glavina, B.Sc. mech. eng. – Inea d.o.o., Stegne 11, Ljubljana
Assoc. Prof. Dr. Mihael Sekavčnik – Faculty of Mechanical engineering, Ljubljana

Faculty of Mechanical Engineering
Aškerčeva 6
SI-1000 Ljubljana
e-mail: andrej.senegacnik@fs.uni-lj.si