REPOWERING OF WASTE HEAT USING ORC IN SLOVENIA

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ABSTRACT

The article deals with ORC (Organic Rankine Cycle) process. This is a working cycle for conversion of low temperature heat into mechanical work. The working fluid is an organic refrigerant. Due to specific properties of refrigerant also the ORC process has some peculiarities. The article presents the ORC process, which will be applied in the Slovenian industry providing a generator power of 120 kW. Some specific features of ORC processes are addressed and the impact of implementation of heat exchangers is analysed. Analysis of the impact of cooling water temperature on the operation of ORC process is also provided.

POVZETEK

Članek obravnava ORC (Organic Rankine Cycle) proces. To je delovni krožni proces za pretvorbo nizko temperaturne toplote v mehansko delo. Delovna snov je organsko hladivo. Zaradi značilnih lastnosti hladiva ima tudi ORC proces nekatere posebnosti. V članku je predstavljen ORC proces, ki bo apliciran v slovenski industriji z električno močjo generatorja 120 kW. Obravnavane so nekatere posebnosti ORC procesov in tudi vpliv izvedbe prenosnikov toplote. Analiziran je tudi vpliv temperature hladilne vode na delovanje ORC procesa.

1. INTRODUCTION

Due to the increasing demand for reduction of environmental pollution on a global scale and reduce the greenhouse effect of fossil fuel use one searches various niches of heat sources to produce mechanical work or electricity. Important but so far ignored sources of heat are waste heat flows from industry processes. These energy sources are usually low and medium temperature flue gases and sometimes also low-pressure steam. Thermodynamics teaches us that it is possible to obtain mechanical work, if there are heat source (hot body), heat sink (cold body) and heat machine with thermodynamic cycle running in it. Sadi Carnot in 1824 discovered one of the fundamental natural laws of limited conversion of heat into mechanical work. Carno'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. Processes with maximum efficiency would run extremely slow with small power and the apparatus would be very expensive. Courzon–Ahlborn's theorem states [2] that due to unavoidable heat transfer irreversibility (limited heat transfer areas and limited time for heat transfer) the thermal efficiency drops additionally 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.

For the purpose of the project the repowering of waste heat in Slovenian industry is foreseen with ORC processes (Organic Rankine Cycle) [1]. Classical Rankine cycles runs between two and two isobaric and isentropic changes of state with phase change of working fluid, which is normally water. In cases where the temperature of heat input is low, water is no longer suitable 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 eg. hydrofluorocarbons, which begin to evaporate at significantly lower parameters (temperature) than the water does. The choice of most suitable organic working media is follows according the temperature boundary conditions of waste heat (heat source) and environment (heat sink) [8].

2. ORC PROCESS IN SLOVENIA

ORC deployment project in Slovenia which is being co-financed by the Slovenian Ministries provides the repowering of low temperature waste heat at several locations in the Slovenian industry. Test launch of the first ORC plant is planned in May 2010. The basic condition, which must meet certain location is sufficiently large heat flux waste heat of about 1 MW, the corresponding temperatures and the possibility of heat extraction from ORC process into the environment. Four possible locations that meet the basic technological requirements in waste heat quantity and temperature level have been investigated for this reason. There are not many relevant sites in the Slovenian industry because we do not have large industry facilities. 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 (the company Calnetix), where the number of appropriate "large" sites is significantly larger.

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 for running the ORC process is supplied with superheated steam. Since the supply of heat is carried out in different thermodynamic processes (heating, evaporation, superheating, ..) is this schematically presented with different elements. In Figure 1, the central part of the plant is marked which is imported from the USA as a whole. It is necessary to design two heat exchangers – for heat input (evaporator) and heat extraction (condenser) according to the available parameters of the heat source and heat sink into the environment.

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

- ORC working media – refrigerant R245 fa - 1,1,1,3,3-pentafluoropropane;

- the parameters of live steam R245 fa at turbine inlet: 16.7 bar, 120 °C condensation parameters: 2.3 bar, 38 ° C
- mass flow of R245 fa: 4.02 kg/s
- electric power of generator: 120 kW
- heat input of water steam: 930 kW
- extracted heat flow to cooling water: 810 kW

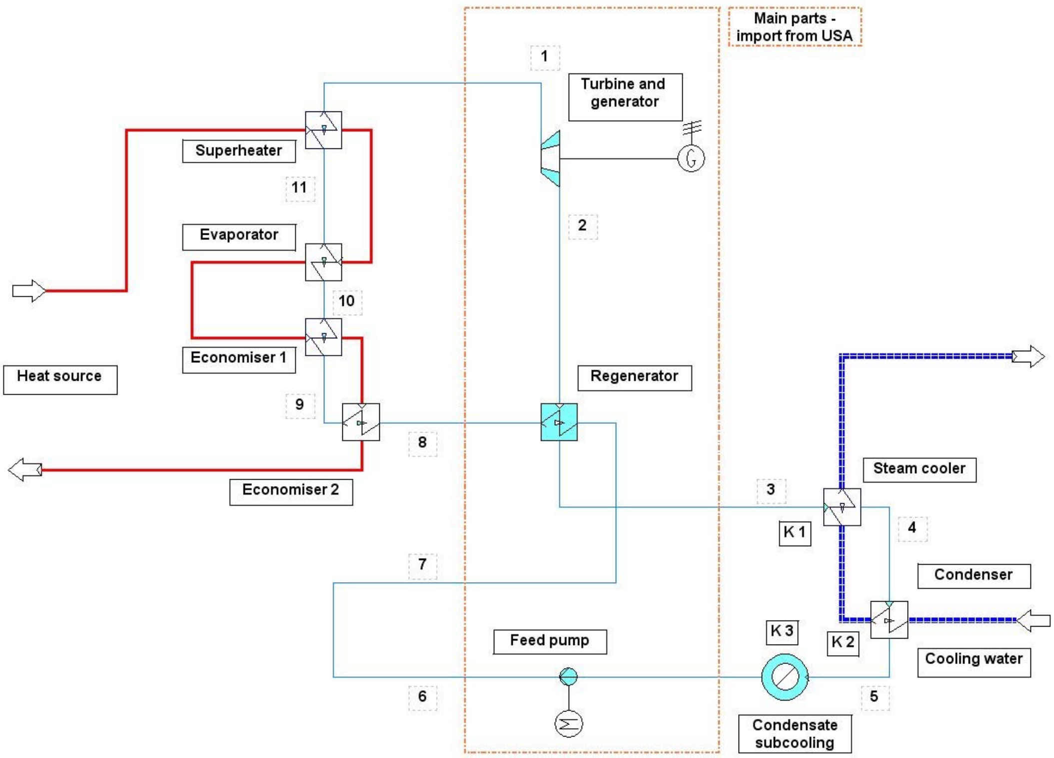

Figure 1: Basic schema of ORC process

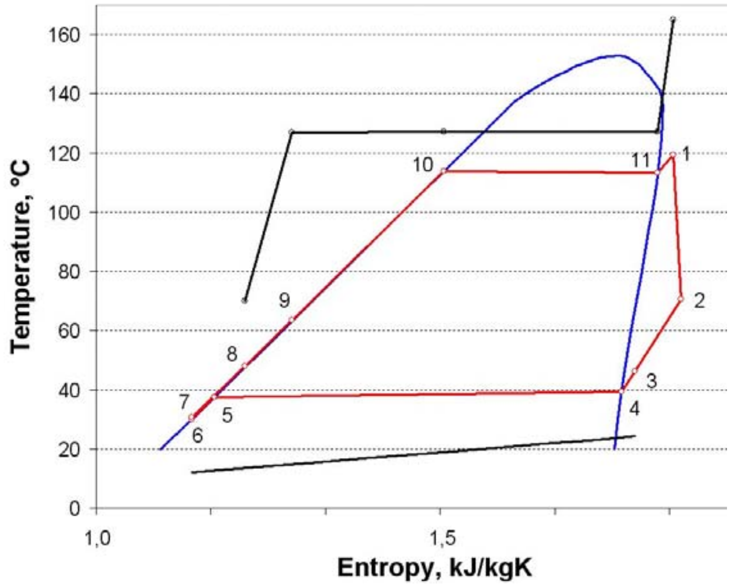

Figure 2: Diagram *T–s* of ORC process

As shown in the diagram *T-s* for the ORC process the working media is characterized by the specific limit curve, resulting in increasingly overheated 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 turbine in the regenerative heat exchanger. This heat is transferred to refrigerant which was firstly condensed and pressurized in feed pump before entry into the evaporator. So this is classical regenerative heat exchange of refrigerant, the difference being that the heating medium does not condense. In the diagram *T-s*, Figure 2, the black lines show the temperature characteristics heat source and heat sink.

2.2 Thermodynamic parameters of ORC process

Figure 3 shows the ORC thermodynamic process with given parameters (mass flow rate, pressure, temperature, enthalpy, steam quality,...). As the heat source the superheated steam with pressure of 2.4 bar and temperature 165 °C is used.

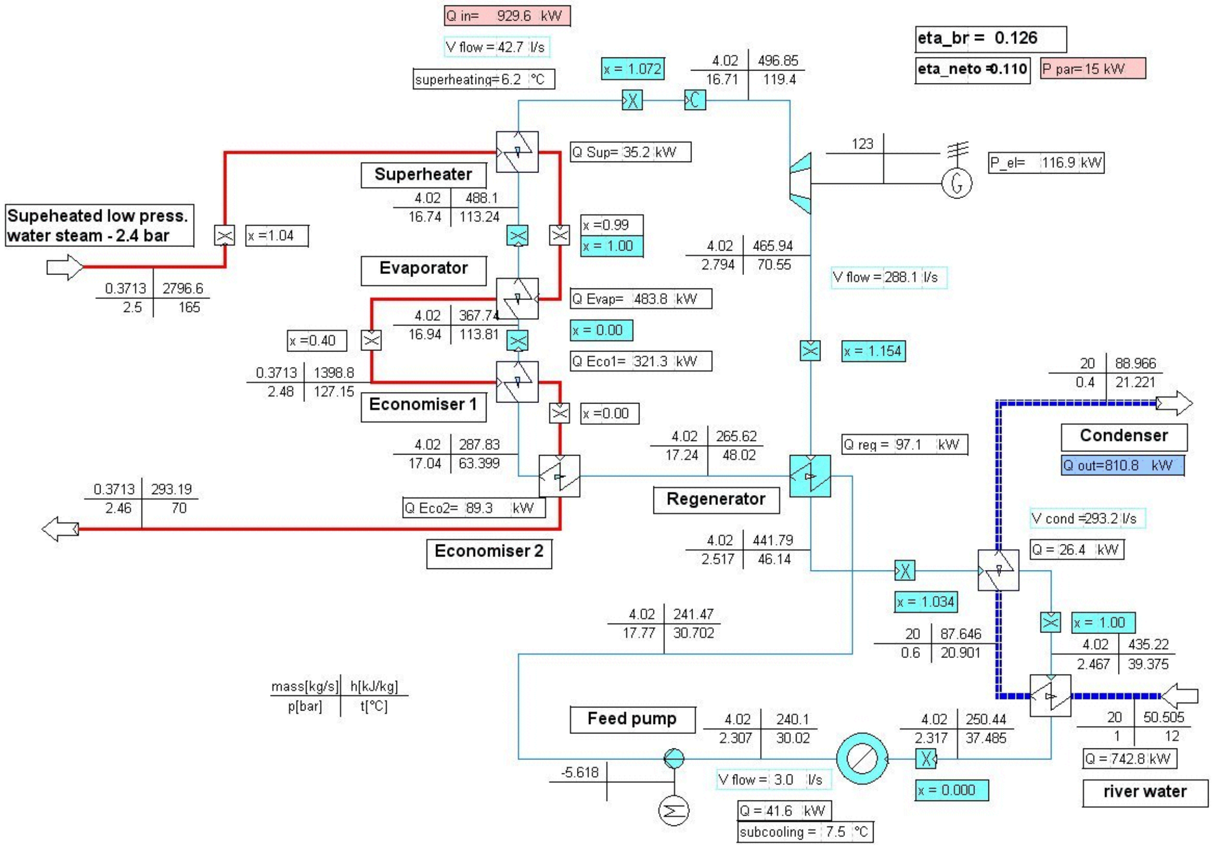

Figure 3: Parameters of ORC plant at generator electric power of 117 kW

The advisability of the use of water steam to drive the ORC is of course questionable, especially when it is extracted steam from industrial CHP. In this case it is justified because the mass flow rate of low-pressure steam turbine work is limited and restructuring of production in recent years leads lack of low pressure steam demand. Efficiency of energy conversion into electricity is, of course, slightly decreased, but is still sufficiently comparable. This applies particularly where the production of electricity from ORC is declared as the "green electricity" (the state guarantees energy trade at guaranteed price), because the primary fuel of steam boiler is wood biomass. When the refrigerant is heated steam condenses. Thermodynamically, these are four different processes and are therefore considered separately; heater 1, heater 2, evaporator and superheater. Similarly, it is also at heat extraction, where we first have steam cooler, condenser, and sub-cooling of condensate. The parameters in Figure 3 were obtained on the commissioning tests of the plant in the U.S.A.

3. SOME SPECIFIC FEATURES OF ORC

3.1 Sub-cooling of condensate

As the electric power ORC processes is relatively small, up to 2 MWe, the relative investment costs in the installed kW of electrical power are already high at baseline. Therefore, the whole plant is supposed to be designed as simple as possible with some standardized elements. Here, the heat exchangers for heat input and heat extraction are meant. For the reasons of simplicity and rentability the plate heat exchangers are often used. Volume flow rate change of organic substances as a consequence of phase change steam-liquid is significantly less than that of water and is therefore in these cases possible to use plate heat exchangers [4, 5, 6, 7]. The negative impact of this simplification is in a very limited impact on the temperature conditions of heat transfer. The very structure of the heat exchanger determines the same mass flow distribution and also during the process of heat transfer it can not be more influenced in any way. In the steam boiler, for example, heat transfer is carried out in several successive heating surfaces with the possibility of intermediate cooling. Therefore, in the case of condensation of refrigerant in the plate heat exchanger inadvertently sub-cooling of condensate is achieved which can go up to 8 °C. If one would like to reduce sub-cooling, the condensation pressure had to be increased greatly and electric power generator would be substantially reduced. Such a real measured example of the condensate sub-cooling of the condensate shows Figure 4. Condensate reaches state at point A, rather than ideal situation at point B, Figure 4. Consequently, one has therefore to bring in the process more heat, which also means lower efficiency.

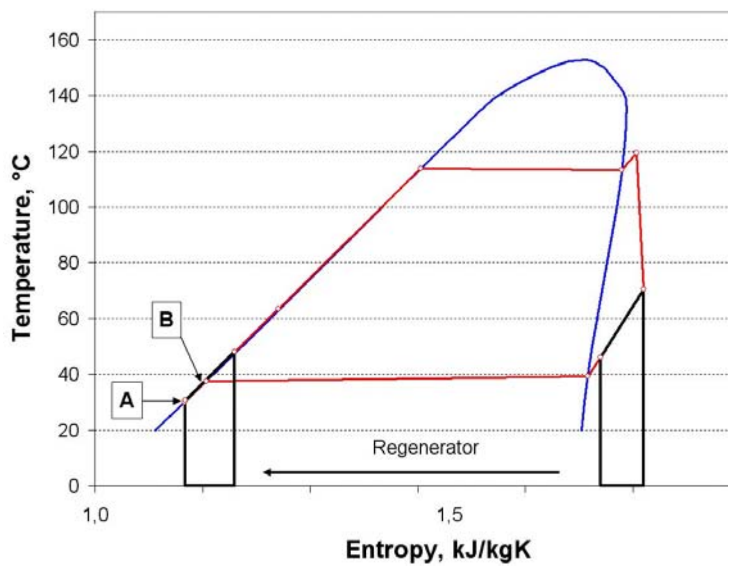

Figure 4: ORC process; regenerative heat flow for sub-cooled condensate of 7.5 °C in point A is lined in

3.2 Heat extraction

Similarly, as with any thermodynamic cycle it is necessary to provide heat extraction into the environment at as a lower temperature as possible. In the case of ORC process this is especially important because the cycle is running in a narrow temperature range. In order to obtain adequate quantities of mechanical work, one must provide adequate enthalpy drop. Regulation process is carried out so that in case of an increase of superheating of live steam at turbine inlet, the pressure of feed pump is increased, thus also live steam at turbine inlet gets increased. As shown in diagram *T-s*, there are no thermodynamic reasons for the superheating temperature rising because the whole expansion in the turbine occurs in the super-heated region. At the same time this leads to increased heat flow (and also its size) which has no sense. The permanent super-heated refrigerant of 5 °C is provided by regulation which prevents the turbine of being eroded by saturated flow erosion of refrigerant R245 fa. It can be seen from the diagram *T-s* that the available enthalpy drop is limited by the pressure of condensation which is a function of the temperature of condensation. Extremely strong influence of cooling water temperature on the operation of ORC process is shown in Figure 5. The simulation of the ORC process was performed with the software package IPSE 4.0. [2].

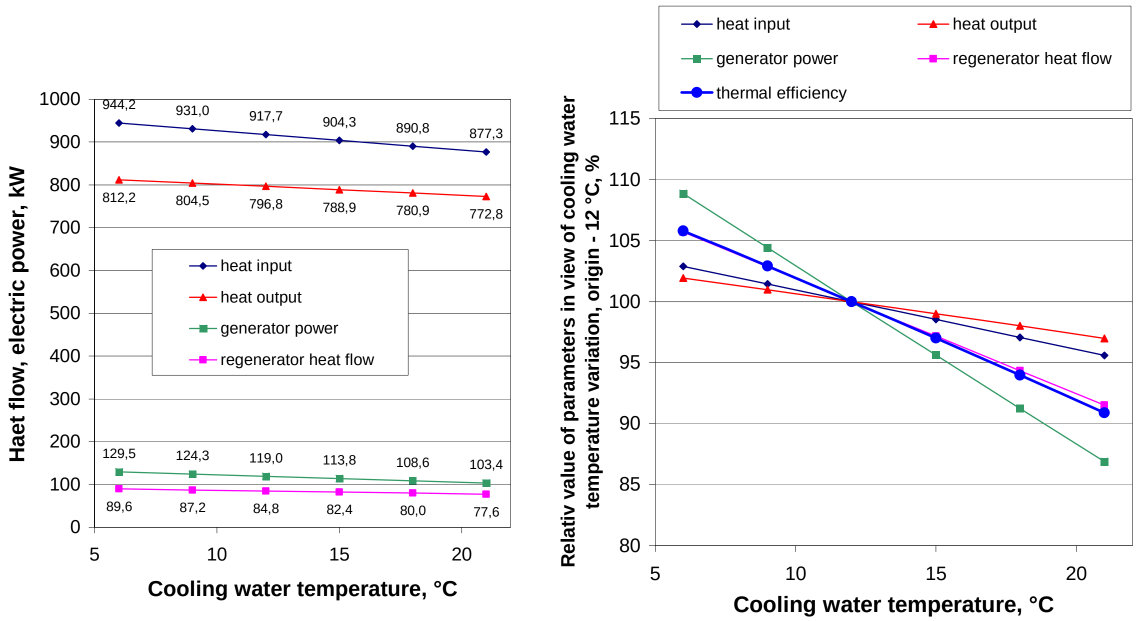

Figure 5: Impact of the temperature of cooling water on the parameters of ORC process

4. CONCLUSIONS

The article deals with ORC (Organic Rankine Cycle) process. This is a working cycle designed to repower low-temperature energy sources - eg. waste streams in the flue gas. ORC process is a classical Rankine cycle process in which instead of water a organic working media – various organic coolants are used. Typical characteristic of organic refrigerant is also a lean saturation curve which makes the steam along the isentropic expansion superheated. Therefore, ORC processes have some special characteristics and differ somewhat from the processes that use water for a working medium. The article presents the ORC process, which will be applied in the Slovenian industry. The basic characteristics of the ORC process are: R245 fa as working medium, the mass flow of 4 kg/s, temperature of steam entering the turbine at 120 ° C, electric power generator of 120 kW input heat flux 930 kW, the efficiency of the process ~ 11%.

Some specific features of ORC process, such as regeneration of heat and impact of the deployment of heat exchangers are explained. The cheapest possible design of plant is provided by standardized plate heat exchangers. These may, on other hand, lead to greater pressure drops and limited possibility of temperature regulation, which may result in a high super-heated steam or sub-cooled condensate. Also the strong influence of cooling water temperature on the operation of ORC process was analyzed.

5. REFERENCES

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