archives
of thermodynamics
Vol. **36**(2015), No. 2, 85–103
DOI: 10.1515/aoter-2015-0017

Selected aspects of operation of supercritical (transcritical) organic Rankine cycle

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Abstract The paper presents a literature review on the topic of vapour power plants working according to the two-phase thermodynamic cycle with supercritical parameters. The main attention was focused on a review of articles and papers on the vapour power plants working using organic circulation fluids powered with low- and medium-temperature heat sources. Power plants with water-steam cycle supplied with a high-temperature sources have also been shown, however, it has been done mainly to show fundamental differences in the efficiency of the power plant and applications of organic and water-steam cycles. Based on a review of available literature references a comparative analysis of the parameters generated by power plants was conducted, depending on the working fluid used, the type and parameters of the heat source, with particular attention to the needs of power plant internal load.

Keywords: ORC; Supercritical power plant; Organic fluid

1 Introduction

Reducing the consumption of fossil fuels in energy production is now a major challenge and a goal not only in terms of research but also politics. This is important due to the overall increase in energy consumption in the world and hence an increase in the emission of pollutants into the environment and decreasing natural fuel resources. One way of enabling, in part, to achieve

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this goal is to use the organic Rankine cycle (ORC) power plants, which in many cases allow to manage low- and medium-temperature energy. The use of this energy type would otherwise be difficult or impossible. The ORC power plants allow for emission-free electricity production from geothermal and solar energy sources, exhaust waste heat utilization or other medium of elevated temperature. An interesting idea might be to use the ORC power plants as a secondary cycle cooperating with a power plant powered by a high-temperature source, in order to increase the overall efficiency of the process. These are just a few examples of possible applications of the ORC power plants, however, there are a lot of possibilities of configuration and modification of the primary cycle, which is another advantage, through which the power plant project can be matched to the characteristics of the particular heat source.

In case of the ORC power plants a variety and the number of substances that can be used as a working fluid may be mentioned as an advantage because the efficiency of the power plant quite largely depends on the appropriately selected working fluid. This gives some freedom when setting up the power plant and creates opportunities for increasing the efficiency of the power plant. It is also possible to combine two or more homogeneous substances in zeo- or azeotropic mixtures and to develop completely new substances which extends even greater versatility of the ORC power plant and provides continuous development perspectives.

Unfortunately, despite many advantages, the main problem of the ORC power plant is the low efficiency of the energy conversion process. That is why the works on the possibilities of its increase are still underway. In addition to the basic methods of increasing the efficiency and power such as increasing the evaporating temperature of the fluid, condensing temperature reduction, vapour superheating, the use of internal heat regeneration, the interesting idea may be the use of the supercritical cycle, which is well known and has been successfully applied to the water-steam power plants. Supercritical cycle in the ORC power plant may be an interesting alternative to subcritical flow, now used quite commonly.

2 Comparison of subcritical and supercritical cycle

The basic diagram of the power plant, which is shown in Fig. 1, in the case of the subcritical as well as supercritical cycle is similar, as both comparative cycles consist of the same thermodynamic processes that is of two isobaric processes and two isentropic processes and to implement them the same devices are used. Differences between subcritical and supercritical cycles can be demonstrated by analyzing for example the process in the T-s diagram, showing characteristic changes for each cycle, as shown in Fig. 2.

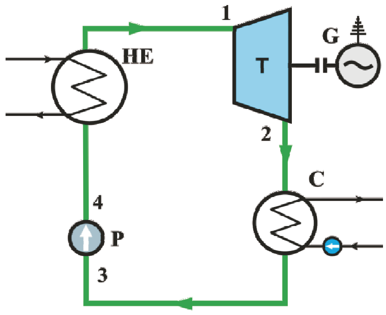

Figure 1: Simplified diagram of the vapour power plant: G – electric generator, T – turbine, C – condenser, p – pump, HE – hear exchanger.

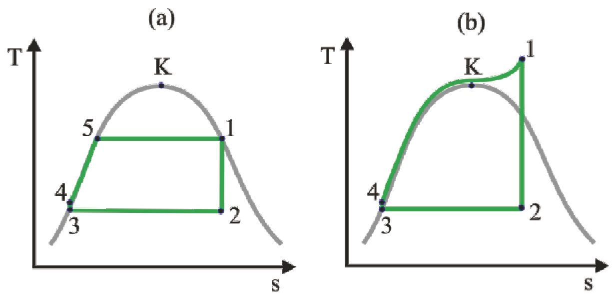

Figure 2: Comparison of 'wet' subcritical cycle (a) with 'wet' supercritical cycle (b) in the T-s diagram.

The main difference is that in the case of the subcritical cycle the processes of heat supply and discharge to/from the cycle run at the pressures below the critical pressure, which causes that at the same time (in part) they run at constant temperatures. While in the case of the supercritical vapour cycle the heat extraction process takes place at a pressure below the critical pressure, whereas the heat input process – at a pressure higher than the critical pressure. Thus, in such cycle the classic process of evaporation does not take place. This cycle may be called a two-phase supercritical cycle, in contrast to a single-phase supercritical cycle known as the Brayton cycle.

One method of increasing the efficiency of the vapour cycles is increas-

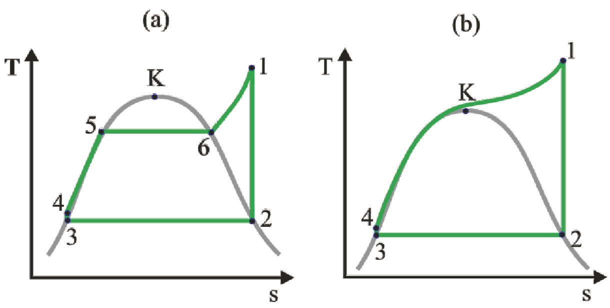

Figure 3: Comparison of a ‘dry’ subcritical cycle using vapour superheating cycle (a) and ‘dry’ vapour supercritical cycle (b).

ing the temperature of the vapour before sending it to the turbine. This procedure can be carried out both in subcritical and supercritical cycles, as schematically shown in Fig. 3.

3 Literature review

The focus in the present work was narrowed down to two-phase supercritical cycles implemented using working media other than water. Bibliography of publications on the use of supercritical cycle in the ORC power plant is quite extensive at present. Researchers are mainly focused on thermodynamic analysis of the ORC power plant operating as supercritical cycle, with particular emphasis on the selection of appropriate operating parameters of the power plant and/or appropriate working fluid depending on the parameters and characteristics of the heat source. Some works concern the comparison of the power plant efficiency depending on the chosen parameters of the heat source and/or the working medium and the comparative analysis of the efficiency of the power plant working on the basis of supercritical cycle and power plants with subcritical cycle. In addition, the literature review includes references to several publications focusing on other aspects of the ORC power plant operation including supercritical cycle, other methods of efficiency increasing, use of zeotropic mixtures, impact of working fluid on the environment, and others.

Due to the diverse nature of the work and various other aspects, which were guided by their authors, in this review the publication analysis was carried out after allocation of works to the following thematic groups:

- heat source analysis,

- working medium,
- power plant efficiency,
- others.

as well as assigning them specific publications and presenting a short summary of the particular thematic group and issues raised in the present work.

3.1 Thermodynamic analysis of the supercritical cycle according to the characteristics of the heat source

Characteristics of the heat source has a significant effect on the operation parameters of the ORC cycle. The sources can be divided into the open sources, e.g., the flow of geothermal water, where only the initial temperature of the heat source is determined and the final temperature is the quantity of the result dependent on the operating parameters of the power plant or the sealed sources, for example, the flow of thermal oil heated in the biomass boiler, in which both the initial and final temperature of the hot source are strictly defined, whereas the parameters of the power plant operation should be adapted to the two parameters of the source. Papers [1] and [2] are devoted to this subject. More popular, however, is the division of research papers because of the heat origin intended for use in the ORC power plant, so in this point a review of works divided into the following subgroups was conducted:

- ORC power plants powered by geothermal energy,
- ORC power plants powered by waste heat,
- ORC power plants powered by solar energy,
- ORC power plants powered by energy from the biomass combustion.

3.1.1 Supercritical ORC power plants powered by geothermal energy

Authors most frequently select geothermal energy as the source of energy to supply the ORC power plant. There may be a lot of reasons for this situation such as general accessibility of geothermal heat, no emissions of pollutants using geothermal energy or other advantages for example little influence of atmospheric conditions on the work of energy sources. The reason may also be, as the authors of [3] reported, that the supercritical cycle using internal regeneration is a very effective method of electricity generation using geothermal energy. This group includes the following publications: [3–6]. Geothermal water temperatures adopted by the authors are different, and moreover, the authors usually do not take a constant value but a range of temperatures for which the calculations are performed. Most articles consider the low-temperature geothermal sources at a temperature not exceeding 120 °C, as shown in works [6,10–12,14–15]. Table 1 summarizes the types of working fluids and values of the ORC power plant efficiency powered by geothermal energy with different parameters presented in various scientific papers.

3.1.2 Supercritical ORC power plants powered by waste heat

The waste heat in many publications is an energy source to supply the ORC power plant. Supplying the ORC power plant with the waste heat has a very high ecological and economical potential because with the development of waste heat the overall efficiency of the processes can be increased and the carrier of waste heat can be both exhaust gases and condenser cooling water, internal combustion engines or the fluid leaving the turbine of the primary cycle. This group includes the following publications: [8,17–22]. The parameters of the considered heat sources are varied, and for example, in [19] hot air at a temperature of 320 °C was applied and in [18] the exhaust gases having a temperature of only 150 °C.

3.1.3 Supercritical ORC power plants powered by solar energy

Solar energy as a heat source to produce electricity is difficult to use because it is subjected to the twenty-four hours periodicity, the radiation intensity varies according to seasons and geographical location, moreover, it is strongly influenced by weather conditions. However, solar energy is used as a heat source for electricity production in cooperation with the ORC power plant. As regards the application of supercritical cycle in the ORC power plant powered by solar it is worth quoting two theoretical studies [23,24], which consider this issue. Particularly interesting conclusions were reached by the authors [23]. They stated that the use of supercritical ORC cycle powered by solar energy gives a higher conversion efficiency than the use of direct conversion using photovoltaic panels.

Table 1: Summary of the types of working fluids and efficiency values in geothermal power plants obtained from research papers by various authors.

Research	Geothermal water temperature [°C]	Subcritical cycle		Supercritical cycle	
		Working fluid	Efficiency [%]	Working fluid	Efficiency [%]
[5]	130–170	Propane (R290), R134a, R227ea, Carbonyl sulfite, R245fa, Isopentane (R601a), water	10.11–10.62	CO_2(R744), R41, R218, R143a, R32, R115, propane (R290), R134a, R227ea	7.97–11.27
[6]	95–120			R125, R134a, R115, propylene	10.5–15.0
[7]	130–170			Propane, R125, R134a	10.2–12.0
[8]	110–160	R134a, R227ea	10.44 – 13.58	R134a, R227ea	7.61–14.13
[10]	100	R134a, R245fa	7.83–7.86	Zeotropic mixture: (R125/R134a, R124/R227ea, R125/R236ea, R125/R245fa), R125	6.82–7.26
[11]	80–120			CO_2, R170, R41, R125, R218, R143a, R115, R32, R1270, R290, R22, R134a, R227ea	6.45–11.55
[12]	100	R134a, R152a, R245fa	7.67–8.52	R125	8.47
[13]	90	R123, R245ca, R245fa, R600a, R236fa, R152a, R227ea, R134a	9.5–11.2	R143a, R218, R125, R41, R170, CO_2	5.2–8.6
[14]	80–120	R245fa	5.8–9.73	CO_2	4.56–8.22

3.1.4 Supercritical ORC power plants powered by the energy from biomass combustion

Biomass combustion is the most common of renewable heat sources to produce electricity using the ORC power plant [8]. At the same time it generates the lowest investment costs. It can be used anywhere where the biomass is cheap and readily available, for example in a sawmill (an example of application is given in [25]). However, there are not many publications devoted to wider use of biomass to supply the ORC power plant with supercritical cycle. Only paper [8] contains some information on this topic, and can be summarised that biomass sources have too high temperature and supercritical cycles are not suitable in that case.

4 Thermodynamic analysis of the supercritical cycle, depending on the working fluid

Selection of the proper working fluid is very important. This is emphasized by many authors of the analyzed publications. In the case of the supercritical cycle, it is important that the critical temperature of the fluid was relatively low and lower than the temperature of the heat source, which is stressed by the authors of [3,26–27]. The authors also often point out that it is important that the working fluid had little impact on the environment and in their papers they give the values of coefficients which are a measure of their impact on the environment, such as ODP or GWP. The example can be Tab. 2, which is part of the table given in [13].

Another important aspect when selecting a working fluid, which is emphasized by the authors of [13,15,28–30] is the heat exchange surface. That is important in particular to heat exchangers of the power plant, which varies depending on the type of fluid. Higher heat transfer surfaces lead to higher investment costs. In the case of the supercritical cycle the required heat exchange surface is often greater than in the case of the subcritical cycle, which can seen from the analysis of Tab. 3 where the values of the heat exchange surface were shown according to the working fluid and the type of the cycle defined by the authors [13].

According to the authors of work [9] an important, but often neglected, parameter of the power plant operation, and to a large extent dependent on the type of working fluid, is a circulating pump work. The pump power is a big part of power station internal load and should be taken into account when calculating the cycle power. The authors of [6] note that the flow rate of the fluid in the case of the supercritical cycle is higher, which may result in an increase in pumping power. In turn, the authors of [3] emphasize that the compression work is lower in the case of agents with a lower critical pressure. The problem of the upper pressure values in the supercritical cycle

Table 2: Environmental properties of working medium defined in [13].

	Substance	Environmental data			Typ of working fluid
		ALT	ODP	GWP (100 yr)	
1	R123	1.3	0.02	77	Isen
2	R245ca	62	0	693	Dry
3	R245fa	7.6	0	1030	Isen
4	R600	0.02	0	∼20	Dry
5	R236ea	8	0	710	Dry
6	R600a	0.02	0	∼20	Dry
7	R236fa	240	0	9810	Dry
8	R152a	1.4	0	124	Wet
9	R227ea	42	0	3220	Dry
10	R134a	14	0	1430	Isen
11	R143a	52	0	4470	Wet
12	R218	2600	0	8830	Isen
13	R125	29	0	3500	Wet
14	R41	2.4	0	92	Wet
15	R170	0.21	0	∼20	Wet
16	CO_2	>50	0	1	Wet

has been presented in [26,14]. Depending on the type of the fluid should be taken into account due to the problems of a technical nature and strength of construction materials. Furthermore, the authors [19] report that the use of working fluids with higher critical temperature, in cooperation with heat sources of sufficiently high parameters, allow for higher vapour temperatures at the inlet to the turbine and allows the use of smaller turbines, which is significant in terms of cost investment. The authors [11] conclude that the most commonly used fluid in supercritical cycles is carbon dioxide (CO_2). This is confirmed by the number of publications in which it is considered as the working fluid [11,13,14,17,20,22–24,31–33] and often the results of calculations obtained for CO_2 are the point of reference for comparing the results obtained when considering other fluids as in the case of works [11,13,17,31–32]. The results obtained by the authors [11] show that the selection of a suitable working fluid has a large effect on the derived parameters of the ORC power plant. Additionally the results obtained for the power plant with CO_2 as the working fluid are not the highest, even

Table 3: Heat exchange surface using different working agents in super- and subcritical cycles [13].

Substance	Turbine inlet temperature [°C]	Area of the heat exchangers [m^2]
R123 (subcritical)	74	12.2
R245ca (subcritical)	74	11.1
R245fa (subcritical)	76	9.2
R600 (subcritical)	72	10.5
R236ea (subcritical)	76	10.1
R600a (subcritical)	76	9.6
R236fa (subcritical)	76	10.4
R152a (subcritical)	74	8.7
R227ea (subcritical)	78	9.0
R134a (subcritical	74	9.6
R143a (supercritical)	84	13.7
R218 (supercritical)	84	21.2
R125 (supercritical)	84	20.8
R41 (supercritical)	79	25.0
R170 (supercritical)	77	23.2
CO2 (supercritical)	84	7.7

though CO_2 is, according to the authors [11], the most widely used agent in the supercritical cycle. Table 4 shows the results obtained in [11] which indicate that the use of agents other than CO_2 in the supercritical cycle can increase the ORC power plant capacity.

Also noteworthy are the works [10,34] in which the authors have attempted to analyze the use of zeotropic mixture in the supercritical cycle. One of the conclusions that have been formulated in [34] is that the use of the azeotropic mixture in the supercritical cycle can contribute to improving the efficiency of the power plant in relation to the case with the subcritical cycle and the unary substance as the working fluid. Similar results were obtained by the authors [10] which can be seen analyzing Tab. 5 being a section of the table with the detailed results presented by the authors in [10].

Table 4: Selected results obtained by the authors of article [11].

Working fluid	Temperature of heat resource (geothermal water)	Working fluid flow rate	Thermal efficiency (+ with or – without internal regeneration	Net power output	Heat transfer capacity	Power of pump to the power of turbine
	°C	kg/s	%	kW	kW/K	%
CO_2	100	0.125	6.45(+)	1.38	5.97	2.32
R170	100	0.08	6.99(+)	1.38	5.98	2.22
R41	100	0.085	6.99(+)	1.59	6.9	2.44
R125	100	0.153	8.64(+)	1.6	5.17	2.38
R218	100	0.281	7.48(+)	1.73	7.57	2.36
R143a	100	0.098	8.88(+)	1.49	4.41	2.42
R115	100	0.141	9.37(+)	1.37	3.9	2.34
R32	120	0.087	10.2(–)	2.56	5.56	2.1
R1270	120	0.058	10.87(–)	2.19	4.72	1.88
R290	120	0.049	11.55(+)	2.08	4.37	1.86
R134a	120	0.085	11.51(–)	1.89	3.65	1.96
R227ea	120	0.235	9.96(–)	2.75	3.96	2.06

Table 5: Some results of calculations presented by the authors of article [10]

Working fluid	Type of cycle	Composition	Turbine inlet temperature	Working fluid flow rate	Net power output	Power of pump	Power of turbine	Efficiency
		Mole frac.	°C	kg/s	W	W	W	%
R134a	sub	1	91.35	0.0185	307.62	29.74	337.35	0.0783
R125/ R134a	super	0.799/0,201	94.23	0.0325	340.29	62.05	432.34	0.0726
R125/ R227ea	super	0.803/0.197	94.97	0.0357	339.31	95.01	434.32	0.0705
R125/ R236ea	super	0.940/0,060	92.98	0.0363	342,39	105,7	448,08	0,0702
R125/ R245fa	super	0.939/0.061	93.65	0.0349	342.96	101.18	444.14	0.0712
R125	super	1	94.09	0.0382	336.46	116.62	453.09	0.0682
R245fa	sub	1	87.40	0.0135	249.91	7.55	257.46	0.0786

4.1 Thermodynamic analysis of supercritical cycle in terms of the power plant efficiency

Comparing the operating parameters of the ORC power plant is not easy because of the variety of factors that may be subjected to comparative analysis. Different authors make different assumptions in the calculations, analyze various configuration variants of the power plant, take various parameters of the heat source and various working fluids. Still, most of them come to the conclusion that the use of supercritical cycle can contribute to improving the efficiency of the ORC power plant.

The authors [8] performed an analysis of the power plant supplied with waste heat coming from the cooling system of internal combustion engines. The working fluid chosen by them was the R245fa working fluid and the calculations were done for the power plant with super- and subcritical parameters. The results obtained, which are given in Tab. 6, confirm that the use of the supercritical cycle can contribute to improving the efficiency of the power plant.

Table 6: Power plant performance results obtained by the authors of [8].

	Subcritical cycle	Supercritical cycle	Relative efficiency gain
Thermal efficiency of ORC	14.62%	15.97%	9.20%
Thermal efficiency of whole system	11.27%	12.72%	12.80%

In turn, the authors of [5] evaluated the efficiency of the ORC power plant supplied with a low temperature heat source, working with 13 different operating fluids (including water) in the super- and subcritical cycles, then the calculation results were compared with each other. In this paper the results obtained for isopentane were taken as a point of reference. The results obtained by the authors are reported in Tab. 7. Analyzing the values listed in Table 7 it can be seen that the results of the net power for the supercritical cycle are higher than those obtained with the use of subcritical cycle.

Comparison of the power plant rating with super- and subcritical cycles was also conducted in [13]. In this work six fluids for the supercritical cycle and 10 fluids for subcritical cycle were considered. The calculation results were presented in Tab. 8.

Table 7: The results obtained by the authors [5] (volumes with asterisk (*) are the results for the supercritical cycle).

Fluid	Temperature of heat resource	Specific net power output	Turbine inlet temperature	Pressure of vapour at the turbine inlet	Net power increase vs. Isopentane
	°C	kW/kg	°C	MPa	%
R744 (CO2)	130	16.56*	110	14	-4.82
	150	25.6*	130	15.6	-9.31
	170	36.34*	150	18	-13.18
R41	130	22.65*	110	10	30.15
	150	34.54*	130	12	22.36
	170	48.29*	150	14	15.37
R218	130	24.21*	100	4.2	39.1
	150	34.73*	122	5.8	23.01
	170	45.56*	142	7.4	8.84
R32	130	21.41*	110	5.8	23.01
	150	36*	130	7.4	27.51
	170	52.99*	150	9	26.6
R115	130	24.58*	96	4	41.25
	150	37.52*	118	5.6	32.92
	170	51.07*	140	7.2	22.03
R290 (propane)	130	19.58	82	3.2	12.54
	150	36.79*	104	4.6	30.3
	170	53.14*	130	6.4	26.97
R134a	130	20.33	78	2.5	16.83
	150	37.48*	107	4.4	32.75
	170	54.73*	133	6.6	30.77
R227ea	130	20.55	80	1.8	18.11
	150	39.84*	114	3.6	41.11
	170	54.75*	138	5.6	30.82
R245fa	130	16.64	74	0.7	-4.38
	150	29.25	86	0.9	3.6
	170	41.8	97	1.2	-0.14
R601a (izopentane)	130	17.4	75	0.4	
	150	28.23	84	0.5	
	170	41.85	92	0.6	
Woda	150	21.59	130	0.05	-23.52

Table 8: Results of the power plant rating obtained by the authors [13].

Fluid	Turbine inlet temperature, °C	Net power output, kW
R123 (sub)	74	5.4
R245ca (sub)	74	5.2
R245fa (sub)	76	4.3
R600 (sub)	72	5.8
R236ea (sub)	76	4.6
R600a (sub)	76	5.1
R236fa (sub)	76	4.7
R152a (sub)	74	5.2
R227ea (sub)	78	3.9
R134a (sub)	74	5.4
R143a (super)	84	6.7
R218 (super)	84	6.9
R125 (super)	84	7.9
R41 (super)	79	9.3
R170 (super)	77	7.2
CO2 (super)	84	2.6

As it can be seen the power plant rating using the supercritical cycle (apart from CO_2) is higher than in the subcritical cycle.

In [12] the authors compared the parameters of the power plant operating according to the supercritical cycle with R125 fluid with the parameters obtained in the subcritical power plant with three different working fluids (R134a, R152a and R245fa). Operating parameters of the power plant and the efficiency of its operation are given in Tab. 9.

The results presented in this paper show that the use of supercritical cycle is not always associated with an increase in both power and efficiency of the power plant. The case of R125 shows that the use of supercritical cycle can lead to an increase in power with a decline in the efficiency of the power plant. The results obtained in [7], which are listed in Tab. 10, are the same.

The authors compared the parameters of supercritical power plant using three working fluids: propane, R125, and R134a. The obtained results show that the best efficiency is obtained using R125 as a working fluid.

In addition, an interesting conclusion was reached by the authors [35] who found that in certain variants of the power plant, where the fluid is evapo-

Table 9: Calculation results obtained in[12].

Working fluid	Unit	R125	R134a	R152a	R245fa
Type of cycle		supercritical	subcritical	subcritical	subcritical
Tcr	°C	66.02	101.06	113.26	154.01
Turbine inlet temperature	°C	91.82	88.86	95.96	68.91
Working fluid flow rate	kg/s	1.496	0.82	0.51	0.789
Pcr	MPa	3.618	4.059	4.517	3.651
Vapor generator rate of heat transfer	kW	203.19	177.77	172.91	172.48
Condenser rate of heat transfer	kW	187.61	162.95	158.18	157.87
Net power output	kW	15.58	14.83	14.74	14.61
Power of pump	kW	4.39	1.17	0.81	0.32
Efficiency	–	7.97	8.34	8.52	8.47

Table 10: Calculation results obtained in [7].

Parameters	Propane	R125	R134a
Condensing temperature, K	320	319	328.4
Condensing pressure, MPa	1.6	2.1	1.5
Inlet pressure of turbine, MPa	6.4	8.4	6
Mass flow of working fluid, kg/s	365	1050	850
Inlet temperature of turbine, K	443.6	407.8	414.8
Power output of turbine-generator, kW	29.04	28.73	27.27
Power input of feed pump, kW	5.69	8.2	4.83
Net power of supercritical cycles, kW	23.3	20.5	22.4

rated in near-critical conditions the capacities achieved may be higher than in the use of supercritical cycle. Similar conclusions, however, for the subcritical cycle are given in [36]. The authors [36] highlight the advantages of the use of the evaporation agent in the near-subcritical conditions and the impact of evaporator work parameters on the efficiency of the ORC power plant.

5 Summary and conclusions

Based on the analysis of the findings in available literature on the application of supercritical cycle in the ORC power plant the following conclusions can be drawn:

- A key aspect of both the supercritical and subcritical vapour power plant operation is the selection of a proper working fluid. In the case of supercritical power plant the selection of the fluid should take into account the adjustment of the working fluid in terms of its critical temperature to the temperature of the heat source.
- The use of supercritical cycle can bring an increase in capacity and efficiency of the power plant but it depends on many parameters such as temperature of heat source or the type of working fluid. Using the ORC power plant on supercritical parameters is usually associated with an increase in efficiency, however, there are cases where the application of supercritical cycle caused a decrease in power plant rating efficiency.
- Implementation of the supercritical cycle may be associated with the necessity for using larger heat exchangers, since the heat exchange surface in the supercritical cycle may be greater than in the subcritical cycle. This has a direct impact on investment costs.
- The use of a supercritical cycle may increase the flow rate of the working medium, which may lead to an increase in circulating pump power. In supercritical cycles the increased pump power also stems from the greater difference in operating pressures in the cycle (the need to go beyond the critical pressure).
- Some working fluids in supercritical conditions have high working pressure, which can lead to construction problems associated with a limited strength of materials.

It should be emphasized that the only work containing the experimental measurements is the paper [23] which provides an efficiency results of the supercritical power plant with CO_2 as the working fluid.

Acknowledgements The work presented in the paper was funded by the National Centre for Research and Development (NCBiR), Poland under the Project No. PBS1/A4/7/2012.

Received 15 January 2015

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