Short Communication

Analyzing Selection of Low-Temperature Medium for Cogeneration Micro Power Plant

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Abstract

This article analyses the ORC system working with dry and wet low-boiling media, which are most frequently used in installations of this type. Two types of cycles were examined: the cycle with heat regeneration for dry media (*fc72*, *hfe7100*, *R227ea*, *R245fa*, *R423a*, and *R600a*) and the cycle without heat regeneration for wet media (*R11*, *R12*, *R134a*, *R718*, and *507a*). The calculations were performed for the assumed required thermal power Q=50 kW and two variants of low-boiling medium temperature equal to t=50 and 95ºC at condenser inlet. The effects of medium type and parameters on basic design parameters of the axial micro turbine also were analyzed.

Keywords: organic rankine cycle (ORC), combined heat and power (CHP), turbine design

Introduction

Systems making combined use of energy conversion devices in such a way that thermal and electric energy is obtained as a result of their cooperation bear the name of combined heat and power (CHP) systems. In practice the efficiency of a CHP system can be higher even by as much as several tens of percent points compared to the same devices working individually, which leads to equivalent reduction of specific consumption of the fuel needed for production of this energy [1]. Profits resulting from the combined operation are enormous and can refer to both large centralized power plants and small units, such as electric power generation sets with power outputs ranging from several to several tens of kilowatts. The operation of power generation devices in cogeneration contributes to the reduction of the production of harmful NO_x, SO_x, and CO_2 compounds, both by reducing the consumption of mineral fuels and utilizing renewable energy sources. Bearing in mind the possible heat recovery, practically at each stage of the power generation system and for arbitrary configuration we can construct an installation consisting of an infinite number of modules. The only limits come from the environmental conditions and economic aspects. Moreover, after the proper adaptation of conventional units, independent power generation sets can be more and more frequently fed with fuels being the products of natural or artificial waste processing. Growing possibilities to utilize materials that could not be utilized in the past makes CHP units more and more attractive. This refers in particular to places in which the availability of conventional solid or gas fuels is difficult. In the case of independent receivers not connected to the power network, this situation additionally eliminates losses connected with the transmission of electric energy [2].

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Low-Boiling Media

The low-boiling media belong to the group of organic substances. As a result, they differ in their molar masses from water, a medium in common use in steam systems. Due to their features, they allow turbine units to work with lower rotational speed and at much lower pressure levels.

A basic advantage of the low boiling media is the low temperature of their boiling. Criteria decisive to their selection are: medium vapour density, thermodynamic characteristics that permit the turbine to obtain maximum possible efficiency or power output, and the ability to secure stable and failure-free operation. In many cases these media can reveal toxicity and flammability. Two types of low-boiling media can be named: the wet media, for which the expansion in the turbine ends in the wet vapour regime, and dry media, with the expansion ending in the dry vapour regime [3-12].

Methodology of Calculations

The object we analyzed was the ORC system working with wet media (*R11*, *R12*, *R507a*, *R718*) and dry media (*fc72*, *hfe7100*, *R134a*, *R227ea*, *R236fa*, *R245fa*, *R423a*, *R600a*). For each above group of media different assumptions were adopted and a different model of the ORC system was used (Fig. 1). In both cases, at the stage of selection of values for characteristic design coefficients, as well as pressures at turbine inlet, p_0 [kPa], and exit, p_1 [kPa], an attempt was made to reach maximal electric turbine efficiency $\eta_{turbine}$ [%] and efficiency in cogeneration η_{total} [%], at the same time preserving the assumed value of the thermal power, $Q_{heating}$= 50 kW. This thermal power was obtained in the heat exchanger through which the cooling water had an inlet temperature of t_5 = 45ºC, the outlet temperature t_6=90ºC, and the same pressure p_5 = p_6 = 600 kPa on both sides flowed at the low pressure side. The turbine power output, N_e [kWe], was the resultant output data.

In the case of wet low-boiling media, a system without overheating was applied (Fig. 1a), for which the values of the coefficients were selected in such a way that the vapour dryness recorded at turbine exit was x_1=1, which testified to the flow of a medium having features of a dry vapour through the turbine. An additional criterion was the temperature at turbine exit. Due to the assumed reception of thermal energy amounting to Q=50 kW from the condenser, this temperature was assumed equal to t_1=95ºC in the first calculation series and t_1=50ºC in the second series. For dry media, the system with heat regeneration was analyzed (Fig. 1b). The regenerator was situated between the turbine and the condenser in which the heat transfer to water took place. In this case the temperature criterion with temperatures equal to t_7=95ºC and t_7=50ºC was adopted directly behind the regenerator.

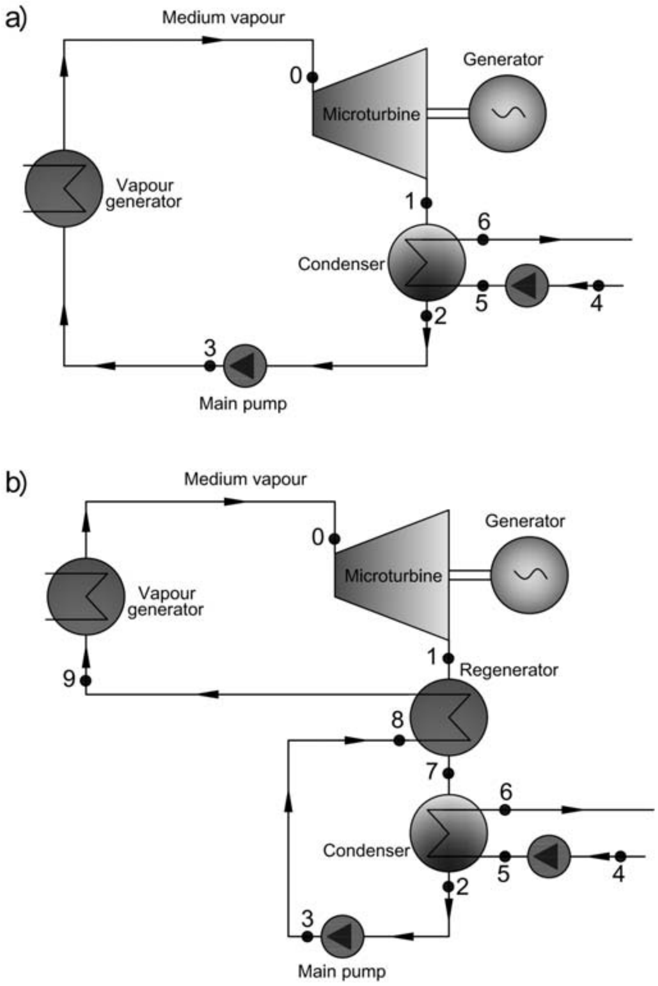

Fig. 1. Scheme of ORC cycle for wet fluids (a) and for dry fluids (b).
0 – vapour turbine inlet, 1 – vapour turbine outlet, 2 – condenser outlet, 3 – main pump outlet, 4 – cooling water inlet, 5 – cooling water pump outlet, 6 – heat exchanger outlet, 7 – regenerator outlet, 8 – regenerator inlet, 9 – regenerator outlet

Table 1. Summary of the results of calculations for ORC cycles and for a single-stage turbine

Parameter/Fluid	ORC cycles						
	$\eta_{turbine}$	η_{total}	$\eta_{turbine}$	η_{total}			
	[%]	[%]	[%]	[%]			
	Temperature in condenser 50ºC		Temperature in condenser 95ºC				
R227ea	8.02	80.27	0.86	79.92			
R236fa	10.34	80.20	4.50	80.23			
R423a	7.69	80.21	0.00	79.77			
hfe7100	18.67	80.17	13.40	80.23			
fc72	16.86	80.11	11.40	80.24			
R245fa	13.39	80.17	7.90	80.28			
R600a	11.83	80.34	6.00	80.39			
R11	3.74	82.42	3.74	82.42			
R12	4.47	82.98	2.67	81.5			
R134A	4.69	83.43	1.29	80.47			
R718	1.35	80.57	1.35	80.57			
R507a	3.93	82.58	7.04	86.35			
Parameter/Fluid	Single-stage turbine						
	ρ	Ma	N_u	ε	ν	η_u	n
	[-]	[-]	[kW]	[-]	[-]	[-]	[rpm]
	Temperature in condenser 95ºC						
R11	0.5	0.6038	2.315	0.8	0.55	0.8973	50000
R12	0.49	0.4959	1.702	0.8	0.5	0.8934	28000
R718	0.5	0.2935	0.8512	0.1	0.5	0.8946	100000
fa72	0.3	0.9936	8.545	0.4	0.6	0.8958	20000
hfe7100	0.2	0.9491	10.09	0.5	0.6	0.8909	37000
R134a	0.1	0.09753	0.2082	1	0.65	0.8778	10000
R227ea	0.1	0.1772	0.5403	1	0.6	0.8841	10000
R236fa	0.4	0.6873	3.104	0.25	0.6	0.8978	22000
R245fa	0.5	0.9885	5.73	0.2	0.6	0.8996	50000
R600a	0.49	0.8329	4.043	0.2	0.5	0.8938	45000
R507a	0.49	0.8623	4.626	0.4	0.6	0.899	60000
	Temperature in condenser 50ºC						
R11	0.55	0.6337	2.244	1	0.49	0.8941	60000
R12	0.55	0.9501	2.609	1	0.5	0.894	65000
R718	0.49	0.3133	0.6478	0.1	0.3	0.859	65000
fa72	0.1	0.9823	8.642	0.8	0.62	0.8851	30000
hfe7100	0.1	0.9943	14.16	0.4	0.65	0.8827	19000
R134a	0.1	0.3604	2.019	0.1	0.8	0.8597	22000
R227ea	0.1	0.6345	5.425	0.1	0.6	0.8849	10000
R236fa	0.1	0.8822	9.751	0.2	0.6	0.8847	35000
R245fa	0.5	1.416	10.05	0.2	0.5	0.8938	55000
R600a	0.15	0.9392	11.21	0.2	0.6	0.8881	65000
R507a	0.49	0.8683	4.57	0.2	0.6	0.8973	50000

$\eta_{turbine}$ – ORC cycle efficiency, η_{total} – cogeneration cycle efficiency, N_u – power turbine stage, η_u – turbine stage efficiency, ν – velocity coefficient, ρ – stage reaction, Ma – Mach number at stage stator exit, ε – supply arc admission, n – rotational speed

Analysis of Results

From among the examined wet media the most favourable results were obtained for *R134a* and *R12*. Only for these two media was there a remarkable increase of turbine efficiency $\eta_{turbine}$, and total efficiency η_{total} was recorded after changing the temperature criterion from t_{1min}=95ºC to t_{1min}=50ºC. The turbine efficiency gains obtained in that way were: $\Delta\eta_{turbine\_R134a}$=3.4% for *R134a* and $\Delta\eta_{turbine\_R12}$= *1.8*% for *R12*. A similar assessment was not possible for *R507a*, as the upper temperature, t_0=70.7ºC, was below the assumed limit t_{1min}=95ºC. Therefore, in the case of this medium the efficiency was only calculated for one assumed temperature. In the remaining cases, due to certain features of the media, the turbine exit temperatures for pressures selected in such a way as to meet the condition x_1=1, higher than t_1=95ºC, and ranged from t_{1R11}=170.7ºC to t_{1R718}=360.5ºC. That is why the efficiency changes resulting from the temperature criterion change are not included for these media (Table 1).

In the case of dry media the highest turbine efficiency was recorded for *hfe7100* and *fc72*. Slightly worse results were obtained for *R245fa* and *R600a*. The highest efficiency gain after changing the temperature criterion was recorded for *R227ea*, when it was equal to $\Delta\eta_{turbine\_R227ea}$=7.16 % , and for *R432a* – $\Delta\eta_{turbine\_R227ea}$=7.69%. For the remaining examined media the turbine efficiency change did not exceed the turbine efficiency level $\Delta\eta_{turbine}$=6%. The worst medium in this respect turned out to be *R423a* (Table 1) [13].

A problem which is to be solved by a micro turbine designer is the very small volumetric flow rate of the working medium, which results in short blades and high rotational speeds [14]. The optimization of single-stage axial micro turbine parameters (reported in the article) took into account circumferential efficiency and circumferential power. The optimized parameters include: velocity coefficient, reaction, rotational speed, and admission arc angle. A parameter that was also the object of assessment was the Mach number. The results of the optimization calculations have been collected in Table 1 [15]. Of certain importance from the point of view of power plant operation is reaching the highest possible electric power of the micro turbine. As a result of the analysis and selection of the design parameters, the most favourable medium in this respect turned out to be *hfe7100*. Promising power outputs were also obtained for *fc72*, *R600a*, *R245fa*, and *R236fa*. Noteworthy is the low sensitivity of *fc72* to condenser temperature changes (the circumferential power keeps approximately the same level of 8 kW). In steam turbines typical values of the velocity coefficient depend on the type of turbine stage and range from 0.4 to 0.5 for impulse stages and approximately from 0.6 to 0.7 for reaction stages [16]. For the analyzed media the velocity coefficient was not larger than 0.7 only in the case of *R134a* was this level exceeded. The stage reaction was selected in such a way that the highest possible circumferential efficiency was obtained, at the same time keeping local reaction values lower or equal to 0.05 at stage hub. In the analysis the stage reaction never exceeded 0.6. The range of the rotational speed obtained for particular media varied widely, from approximately 10,000 rpm to as much as 100,000 rpm. Unfortunately, in most cases it was not possible to reach the full admission arc, and in some cases it did not exceed 20%. The design parameters were selected in such a way that the Mach number did not exceed one and in most cases subsonic stages were obtained, with one exception when the supersonic flow was recorded.

Conclusions

Our analysis has proven that the most favourable medium from the point of view of circumferential power of the stage is *hfe7100*. Satisfying circumferential powers were also obtained using *fc72*, *R236fa*, *R245fa*, and *R600a*, especially when the condenser temperature dropped from 95ºC to 50ºC. That is why the above five media were given a more detailed analysis. The optimal velocity coefficients were at a typical level from 0.5 to 0.6, irrelevant of the condenser temperature level. Taking into account the rotational speed, the most favourable media were *hfe7100*, *fc72*, and *R236fa* (for which the rotational speed ranged from approximately 20,000 to 35,000 rpm), which is not a serious technical and technological problem at present. The small value of the admission arc (about 0.2) for *R236fa*, *R245fa*, and *R600a* decreases their attractiveness, as compared to *hfe7100*, for instance, for which the obtained admission arc was equal to 0.5.

Almost all these media secure reaching the Mach number smaller than one, only for *R245fa* and the condenser temperature equal to 50ºC the Mach number remarkably exceeded 1. The performed thermodynamic and technical assessments have shown that the most favourable medium is *hfe7100*. However, in the case the technical realization of a micro turbo set is planned, other criteria should also be taken into account, including medium toxicity (safety in case of possible leakage) and the effect on the environment. A detailed and reliable economic analysis is also to be performed. Final selection of a pro-ecological medium will be a compromise between its advantages and disadvantages.

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