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Gas boiler as a heat source for a domestic micro-CHP

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Abstract

This analysis considers a commercially available domestic gas boiler as a heat source for a domestic organic Rankine cycle system. An experimental study was made into the applicability of the gas boiler (De Dietrich with thermal power 25 kW) coupled with the laboratory prototype micro ORC setup. The main aim of the study is to determine the working fluid temperature, attainable heat rates and efficiencies of the whole system. Preliminary investigations show that the boiler was able to provide saturated/superheated vapor of ethanol and HFE-7100 as a working fluid at the required conditions needed in the ORC system and it can be utilized as a heat source in a domestic micro-CHP. The results should encourage future development of micro cogeneration units.

Keywords: Micro CHP, organic Rankine cycle, gas boiler

1. Introduction

Recent years have seen increased interest in distributed generation, based on local energy sources, and technologies utilizing both fossil fuels and renewables. Generation of electricity on a small domestic scale—together with production of heat—can be achieved through using gas engine units, micro gas turbines, fuel cells with efficient electrolysis, Stirling engines or organic Rankine cycle (ORC) systems. At the time of this paper the authors are involved in a large scale project tasked with developing a commercially viable combined heat and power (CHP) unit based on ORC technology for domestic applications. The ORC is one of the technologies advised for implementation by EU Directive 2012/27/EU.

The operating principle of a system implementing ORC closely follows the fundamental principles of the classic Clausius-Rankine cycle (C-R). The main difference between these two cycles is the working fluid applied. In the case of ORC the working fluid is an organic compound instead of water, which is used in the classical Rankine cycle. In CHP systems based on organic fluids, the operating temperatures and pressures of the working fluid are lower than in the conventional steam C-R systems. Therefore ORC technology is safer for users, which is important in the domestic environment.

Practical realization of the ORC cycle on a micro-scale is a technical challenge. In micro-CHP the electric power production is below 10 kW_e. The system is equipped with various constituent devices such as the heat source (boiler), expansion device and heat exchangers. Each of them should be of high performance individually and the system as a whole should work efficiently.

The heat source in CHP can be of various origin. For example [1] have done experimental investiga-

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tions of a biomass-fired micro-CHP adopting ORC technology. In these investigations, the preliminary tests of the system were carried out with a 9 kW electric boiler and subsequently with a 25 kW_{th} biomass boiler. The maximum electric power produced by the unit driven by the electric boiler was only 96 W_e. The biomass boiler was then used and this led to higher electric power generation of 284 W_e. In this case electrical efficiency was 1.34% and thermal efficiency was about 88%.

A micro-CHP unit combined with a solar-gas system was developed by [2]. Their installation consisted of evacuated tube collectors and a gas condensing boiler, with a nominal thermal power of 25 kW_{th}. Two working fluids were tested, namely n-pentane and HFE-301. The results showed that HFE-301 is superior to n-pentane as regards lower boiler temperature requirement, higher isentropic efficiency of the expander and higher electrical cycle efficiency.

Qiu and Hayden [3] analyzed the thermoelectric power cycle with ORC in the framework of micro-CHP systems. Refrigerant R245fa was applied as a working fluid for the ORC module. An experimental setup was built and mathematical modeling was employed to investigate the efficiency of power generation using the dual-cycle system. The authors achieved electrical efficiency of 17%. Thermoelectric modules and converters were found to be able to integrate with the micro-CHP.

In the literature there are a limited number of papers devoted to the development of ORC–based micro–CHP systems. These systems are able to partially cover the electricity demands of residential buildings. Such applications will achieve better fuel utilization, reduced emissions and lower running costs.

This paper considers a domestic gas boiler as a prospective household application. The boiler was coupled with a laboratory scale prototype micro ORC unit. The setup was experimentally investigated with the application of two working fluids. The main aim of the study was to determine the working fluid temperature, attainable heat rates and efficiencies of the whole system.

2. Experimental facility

The experimental activities aimed to develop a prototype realizing the ORC cycle based on commercially available boiler as a source of heat, as shown in Fig. 1. The thermal oil Mobiltherm 603 was used in the heating circuit of whole system. Its features include: good thermal durability, high resistance to oxidation, good properties in the indirect heating system at working temperature to about 315°C and non-toxicity. The producer supplied the thermodynamic and transport properties of the oil for the calculations.

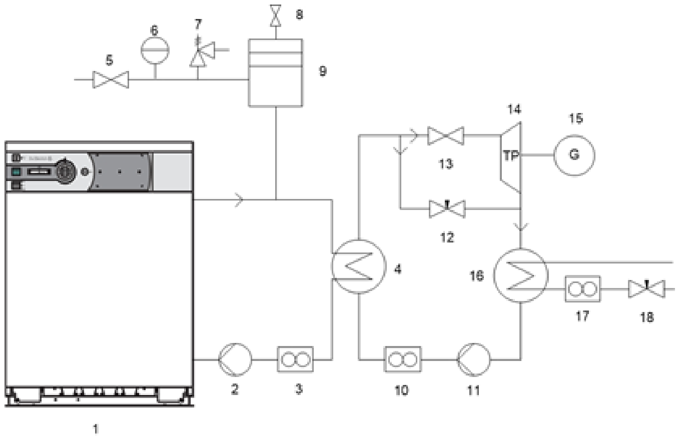

Figure 1: Laboratory installation; 1—gas boiler De Dietrich, 2—oil circulating pump, 3—oil flowmeter, 4—evaporator, 5, 8, 13—ball valve, 6—manometer, 7—safety valve, 9—compensation vessel, 10—mass flowmeter, 11—working fluid pump, 12—throttle valve, 14—expander, 15—alternator, 16—condenser, 17—water meter, 18—throttle valve

The source of heat for the thermal oil was a DTG gas boiler manufactured by De Dietrich. It was adapted to work with thermal oil at high temperature [4]. The nominal thermal power of the boiler was 25 kW [5]. The gas boiler featuring an open combustion chamber was equipped with electronic ignition with ionization flame control and an atmospheric burner adapter for burning natural gas and liquefied petroleum gas (LPG).

The thermal oil circulated in a closed loop between the boiler and evaporator, which is a common part of the CHP-module. Circulation was provided courtesy of a Wilo ST20/6-3C pump with a maximum capacity of 3.5 m^3/h and maximum head of 6 m. This kind of pump is capable of working with high temperature media and is used in solar systems. Preliminary overpressure in the oil circuit, recommended by the producer, was obtained by introducing nitrogen to the compensation vessel. In the "cold" system the overpressure was kept at 0.5 bar. The oil circuit was equipped with a safety valve of 3.5 bar opening pressure.

Ethanol and HFE-7100 were selected as potential working fluids on the basis of earlier considerations. These fluids have relatively good thermodynamic and heat transfer characteristics and fulfill most of the requirements facing the prospective working fluids for such applications.

Evaporator and condenser duties in the ORC cycle were provided by plate heat exchangers manufactured by Secespol, with heat transfer surfaces of 1.8 m^2 (LB47-40 PCE) and 0.9 m^2 (LB47-20 PCC) respectively, corresponding to the capacities of 15 kW and 11 kW, respectively. The test facility was assembled in such a way that incorporation of the expanding device was straightforward and easy.

The flow of working fluid (ethanol/HFE-7100) was accomplished in a closed loop of ORC and was forced by the positive-displacement pump system. The pumps (HP 0815004) were electrically supplied and connected in series. The maximum available flow rate was 0.1 kg/s, the maximum pumping pressure up to 24 bars. The flow rate was controlled by voltage adjustments or by a manually operated throttle valve. The throttle valve was mounted in a bypass circuit.

The working fluid passing through the evaporator received heat from the thermal oil (Mobiltherm 603) and evaporated. It was the intention of the experiment to reach the inlet parameters to the expanding machine at the pressure level of up to 7 bar and temperature of 180°C, preferably as close as possible to the vapor saturation line. If the rate of heat was large enough, the working fluid reached the superheated vapor state. The saturated/superheated vapor was directed to the expander, where it performed work and then the used vapor went to the condenser. The latter was cooled by tap water, having known parameters at the inlet. Following the change of phase in the condenser, the refrigerant was directed to the storage tank.

The function of the expander in the micro-CHP was performed by the pneumatic wrench (VS02YU1260T model), which was specially adopted to be suitable for the experimental demand [6]. Its basic technical parameters were: rotational speed 6500 rev/min, torque 813 Nm at the supply pressure of 7 bar (air), air flow rate demand of 0.36 m^3/min, weight 2.8 kg. Such nominal parameters of operation made it a very attractive option for implementation in the ORC. The body of the device was made of steel. The essential part of applied pneumatic device was the vane engine. The expander was connected by a belt transmission with a standard car alternator. The accumulator (12 V, 55 Ah) with variable resistor was connected to the alternator circuit.

The temperature in the characteristic places of the circuit was measured by a K type thermocouple of class one accuracy. The thermocouples were connected with the CROPICO 3001 acquisition system, which had an internal reference temperature stabilizer. The temperature in the tank of HFE-7100 liquid was measured by a PT100 transducer working with an SRT-73-1321 temperature controller. The volumetric flow rate of the thermal oil was determined by the PoWoGaz JS130-3.5 rotary-vane meter with minimum graduation, which was admitted by the producer to work with thermal oil at temperatures up to 130°C. The Coriolis mass flowmeter SITRANS FCMASSFLO 2100 together with signal converter was used to measure the flow rate of the micro-CHP working fluid. The accuracy of the measurement readings was 0.1%. The water volumetric flow rate was measured by Magflo (MAG 3100) electromagnetic flowmeter with an accuracy of 0.5%.

3. Working fluids

Chemically clean ethanol was selected as the first working fluid in the ORC circuit equipped with a "domestic" gas boiler. Its physical properties, required in the thermal calculations, were taken from the Refprop v 9.0 software [7]. Ethanol is considered a "wet" working fluid due to the slope of the vapor saturation curve.

Novec^{TM} HFE-7100 offered by 3M was considered as a second working fluid in the ORC circuit. It is a solvent from the HFE family with the chemical formula $CH_3OC_4F_9$. HFE-7100 is ozone-friendly. It may be applied as a washing agent and also as a carrier of thermal energy. Due to the vapor saturation curve, it is called a "dry" medium, which is important for application in the ORC circuit. A "dry" medium indicates the need for a recovery heat exchanger in the system. HFE-7100 is non-combustible, non-explosive and non-toxic for humans, which is certified by the producer at the average concentration below 750 ppm in the work environment and during 8 h/day exposure [8]. The main drawback of this fluid is the non-negligible probability of its thermal decomposition at high temperatures.

The thermo-physical properties of both analyzed fluids are listed in Table 1.

Table 1: Properties of ethanol and HFE-7100

Parameter	Ethanol	HFE-7100
Molecular weight, kg/kmol	46.1	250
Normal boiling temperature, °C	78.2	61
Freezing temperature, °C	–107	–135
Critical temperature, °C	241	195
Critical pressure, bar	61.5	22.3
Density of liquid (at 25°C), kg/m^3	785	1,520
Density of vapor (at 25°C), kg/m^3	0.15	2.86
Heat capacity of liquid (at 25°C), kJ/(kg·K)	2.57	1.25
Heat of vaporization (at 1 bar), kJ/kg	851	112
Surface tension of liquid (at 25°C), mN/m	21.8	13.6
Viscosity of liquid (at 25°C), mPa·s	1.08	0.61

4. Experimental results

The results of experimental investigations using both working fluids are presented in Table 2. The table sets out the example measurement results obtained for the evaporator in the ORC circuit.

The following values were determined in the course of experiments: evaporator capacity (Q_{ev}), internal power of expander (N_t), electric power generated in the alternator (N_{el}), cycle thermal efficiency (η_t), which was evaluated without taking into account the work necessary for pumping, maximum Carnot efficiency (η_C), internal efficiency of the expansion machine (η_i), exergetic efficiency (η_b) and finally the electric efficiency (η_{el}) of the device. Table 3 shows the calculated values of the power and efficiencies. The internal efficiency of the expansion machine was determined from the well-known relation:

$$\eta_i = \frac{h_1 - h_2}{h_1 - h_{2s}} \tag{1}$$

where: h is the specific enthalpy [J/kg], h_s is the specific enthalpy after adiabatic expansion [J/kg]. In Eq. 1 state 1 denoted the inlet to expander, state 2 – the outlet and 2s – the state after adiabatic expansion, Fig. 2. The Carnot efficiency, $\eta_C = 1 - (T_2/T_1)$, and exergetic efficiency. In all cases state 1 was found in the superheated vapor region.

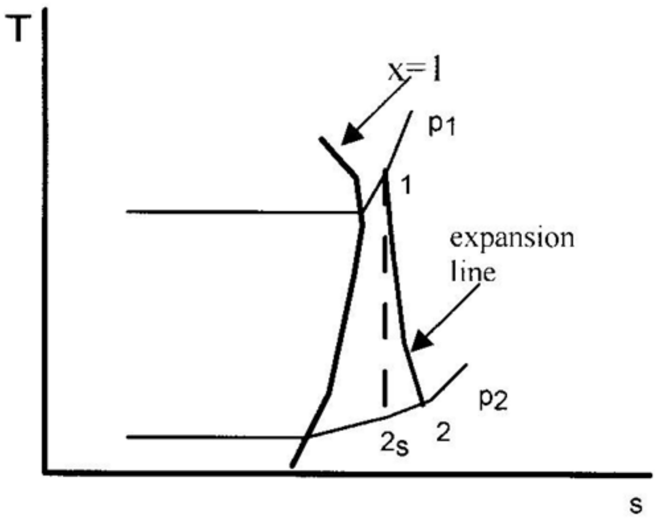

Figure 2: Determination of internal efficiency of expander

In the case of the HFE-7100 medium the theoretical efficiencies of the cycle, in the authors' opinion, were low but they corresponded to the published data. For example Qiu [9] obtained 4% ORC cycle efficiency with HFE-7000 working fluid. They emphasized that the efficiencies for the HFE-7100 medium could be even lower. It should be pointed out that Qiu utilized the expander, which was also constructed on the basis of the vane motor. The HFE-7000 vapor parameters obtained by Qiu [9] were as follows: live vapor temperature of about 120°C and pressure of about 6.5 bar, which were very similar to the parameters obtained by the authors on their own experimental set-up.

During the investigations a negative influence of the HFE-7100 medium on the Teflon seals used in the expander was noticed. This effect strengthened as the operating temperature rose. After about 4 hours of operation the friction resistance in the bearing seating stopped the expander, demonstrating that the expansion device should be replaced.

5. Conclusions

The paper presents experimental investigations into a micro-CHP ORC developed in-house. At this stage attention is placed on an adapted DTG gas boiler by De Dietrich and two media used as the working fluids, namely ethanol and HFE-7100. The system was tested with a pneumatic wrench, used for the expansion work.

During the experimental research with ethanol as a working fluid in the ORC, the gas boiler generated saturated/superheated vapor with temperature of up to 150°C and pressure up to 7 bar, when the ethanol mass flow rate was at the level of 0.022 kg/s. 160 W_e of direct current electric power was generated, although the expander experienced technical problems (excessive heating and increase in frictional resistance in the bearing seatings). The issue of the expander remains unresolved. A solution based on a pneumatic wrench seems unsatisfactory. At present a novel and original design of an axial 7-stage turbine is undergoing testing.

The mechanical and thermal strength of the modified De Dietrich DTG gas boiler was demonstrated for the thermal oil, which worked in temperatures up to 180°C. The maximum thermal power carried by the oil in the evaporator or the ORC circuit filled with ethanol was about 24 kW. These results proved the usability of an adapted boiler as an independent source of heat. In the authors' opinion the gas boiler that was used can be considered a prospective source of thermal energy for a domestic micro CHP. Producers of gas boilers should seriously consider the possibility of manufacturing gas boilers with ORC modules.

Acknowledgments

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References

[1] H. Liu, G. Qiu, D. F. Shao, Y and, S. Riffat, Preliminary experimental investigations of a biomass-fired micro-scale chp with organic rankine cycle, International J. Low-Carbon Technology 5 (2010) 81–87.

[2] W. Yagoub, P. Doherty, S. Riffat, Solar energy-gas driven micro-chp system for an office building, Applied Thermal Engineering 26 (2006) 1604–1610.

[3] K. Qiu, A. Hayden, Integrated thermoelectric and organic rankine cycles for micro-chp systems, Applied Energy 97 (2012) 667–672.

[4] D. Mikielewicz, J. Wajs, R. Bieliński, Z. J., Adaptation of gas boiler for thermal oil application, Internal report PAS, 578/2011, Gdańsk [In Polish].

[5] Producer data, De Dietrich.

[6] D. Mikielewicz, J. Mikielewicz, J. Wajs, Experiences from operation of different expansion devices for application in domestic micro chp, Archives of Thermodynamics 31 (2010) 3–13.

[7] NIST Reference Fluid Thermodynamic and Transport Properties – REFPROP v 9.0, 2010.

[8] Producer data, 3M Company, 2011.

[9] G. Qiu, Y. Shao, J. Li, H. Liu, S. Riffat, Experimental investigation of a biomass-fired orc-based micro-chp for domestic applications, Fuel 96 (2012) 374–382.

Table 2: Evaporator balance

	$\dot{m}$ g/s	t_{in} °C	t_{out} °C	p bar	Q_{et} kW	$\dot{m}_{oil}$ g/s	$t_{ol_{in}}$ °C	$t_{ol_{out}}$ °C
Ethanol	22	37.4	147.9	7.03	23.62	263	180.0	142.0
	21	31.1	137.0	6.78	22.41	263	175.0	139.7
	19	27.2	140.7	6.63	20.65	263	171.5	138.3
	19	22.6	140.7	6.73	20.86	263	170.8	137.2
HFE-7100	47	20.3	144.2	6.44	10.96	220	155.0	128.9
	48	18.6	156.0	6.44	11.92	220	167.0	141.1
	49	17.1	159.6	6.44	12.45	220	173.0	147.0
	50	16.2	154.8	6.49	12.48	220	165.7	142.0

Table 3: Calculated values of power and efficiencies

	$\dot{m}$ g/s	$\dot{Q}_{ev}$ kW	N_t kW	N_{el} kW	$\eta_t = N_t/\dot{Q}_{ev}$ %	η_C %	η_i %	η_b %	$\eta_{el} = N_{el}/N_t$ %
Ethnanol	22	23.62	1.637	0.161	6.93	28.3	84.9	24.5	9.84
	21	22.41	1.071	0.124	4.78	25.8	61.2	18.5	11.57
	19	20.65	1.134	0.129	5.49	28.7	69.5	19.1	11.37
	19	20.86	1.060	0.119	5.08	29.3	63.6	17.4	11.23
HFE-7100	47	10.96	0.677	0.050	6.18	29.76	81.36	20.76	7.38
	48	11.92	0.672	0.046	5.64	32.32	74.87	17.44	6.84
	49	12.45	0.348	0.046	2.79	33.34	37.17	8.38	13.22
	50	12.48	0.320	0.050	2.56	32.85	33.51	7.80	15.63