CASE STUDY OF AN ORGANIC RANKINE CYCLE (ORC) FOR WASTE HEAT RECOVERY FROM COGENERATION SYSTEMS

Talieh Rajabloo[1]
[1]EnergyVille, 3600 Genk, Belgium
(talieh_rajabloo@yahoo.com)

*Corresponding author e-mail: talieh_rajabloo@yahoo.com

ABSTRACT

The major part of wasted heat at industrial sites are suitable sources for low temperature Organic Rankine Cycles (ORC). Integration of ORC with combined heat and power (CHP) plants to produce more electricity is a valuable technology to recover the wasted heat. In this study the thermodynamic assessment of such a integration was explored taking the actual waste heat properties into account. An existing CHP in Flanders was considered as the study case. The outcomes of this study demonstrate power production and cycle efficiency of ORC utilizing waste heat from the selected CHP. Moreover, due to the variety of CHPs spread in Flanders and environmental rules on water consumption at industrial sites, different types of cooling resources were investigated to clarify the most suitable cooling option at different ambient conditions. The results of cooling systems for two types of dry and adiabatic air coolers are demonstrated in the current study. Then, dimensional and sensitive analysis on the effect of ambient temperature on cooling systems were accomplished. Based on these results the suitable range of ambient temperatures to run dry air coolers are reported in this work.

1. INTRODUCTION

Waste heat is one of the important energy losses which has attracted attention to be captured and utilized or to be converted into electricity. As for the conversion concept, ORC is a developing technology (Oyewunmi, Pantaleo et al. 2017, Rajabloo 2017, Al-Tameemi, Liang et al. 2019, Arabkoohsar, Nami et al. 2019, Chatzopoulou, Lecompte et al. 2019). ORC systems have potential to generate electricity from renewable energy sources as well as to enhance industrial energy efficiency. In reality, the waste heat is available from different industrial sources such as flue-gas exhausts, offshore oil and gas processing platforms, kilns in the cement and steel industries and also combined heat and power plants (CHP) (Oyewunmi, Pantaleo et al. 2017, Rahbar, Mahmoud et al. 2017, Agathokleous, Bianchi et al. 2019, Delpech, Axcell et al. 2019, Liao, Liu et al. 2019, Omar, Saghafifar et al. 2019, Yue and Wang 2019). As another case, Low-temperature flue gas produced by a liquefied petroleum gas (LPG) stove was used as the heat source to simulate industrial flue gas, and its temperature can be controlled in the range of 90-220 °C (Zhou, Wang et al. 2013).

Several studies show the potential of combined heat and power technology in energy intensive sectors. As an example, Alipour (Alipour, Mohammadi-Ivatloo et al. 2015) concludes that the profitability of these CHP plants can be improved by selling excess heat to nearby customers.

In order to utilize waste heat from CHP as a heat source for ORC both the quality of waste heat from the CHP and the availability of suitable cooling resources are important parameters which should be investigated further. For an installed CHP, the ambient temperature and the availability of cold water nearby can play a key role on the viability of ORC application. Several studies investigated different cooling systems for ORC (Chaiyat and Kiatsiriroat 2015). As a case in point, M. Usman et al. (Usman, Imran et al. 2017) compared a cooling tower and air coolers for Ulsan and London areas. They reported that cooling tower based system are preferable for hot dry regions while dry air-cooled systems can be implemented for Ulsan and London.

In this study the possibility of an ORC driven by waste heat from a CHP plant has been investigated thermodynamically. A bio based CHP installation with Jenbacher gas engines (JMS 420 GS-B.L Biogas

1.415kW el.) was selected as a case study and its waste heat properties were considered as input to the model of an air cooled ORC plant. The exhaust gas temperature of the selected CHP plant at full load is 427 (°C) in which the recoverable temperature for ORC can, roughly, be 180 (°C). Next, an adiabatic cooling system was investigated. The dry and adiabatic air coolers were investigated more in detail in order to find the effect of the different parameters on the performance of the cooling systems. More cooling options will be considered in the future work.

2. HYBRID PLANTS

In this section, first, the installed CHP's in Flanders are reported. Then, the viability of capturing waste heat from a selected CHP is studied. Finally, cooling methods are investigated to find the most appropriate option since cooling system selection is case dependent and an important issue to tackle.

2.1. CHP and ORC

The quality of waste heat from existing CHP systems in Flanders can be considered as a first selection criteria for the installation of ORC. Figure 1 shows the location of CHP in Flanders by power class.

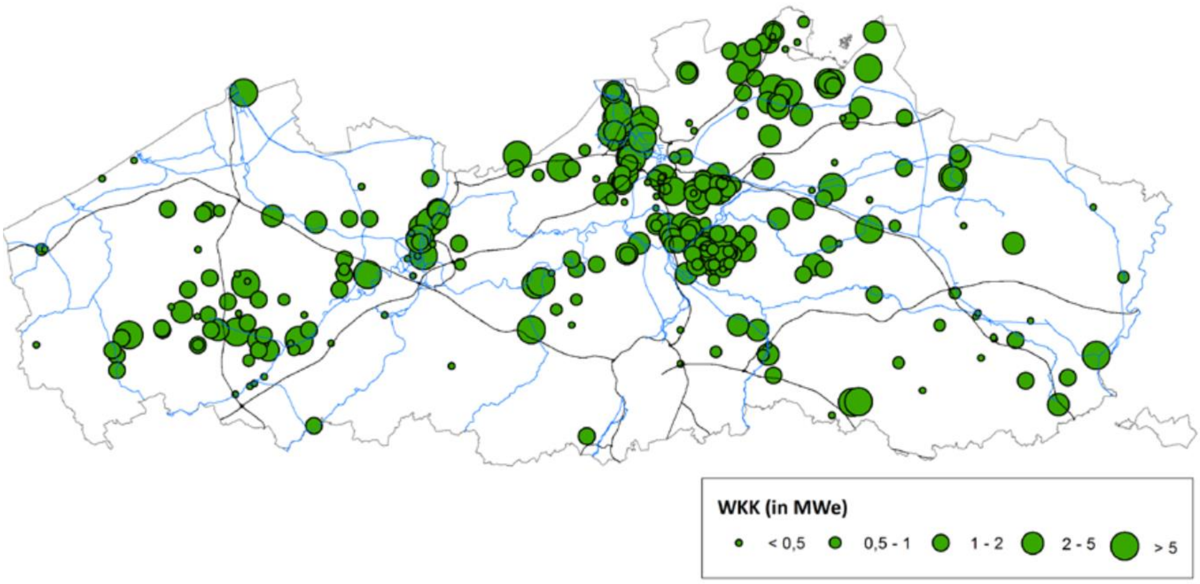


Figure 1: Overview of the location of the CHP in Flanders by power class

The dispersion of CHPs results in different cooling scenarios for the possible ORC installation at each case depending on the availability and cooling efficiency. Therefore, after a thermodynamic exploration on the assessment of ORC, the next step is to detect the best cooling option. Figure 2 depicts a schematic combination of ORC and CHP. And, Table 1 shows the properties of the waste heat from the studied sample CHP.

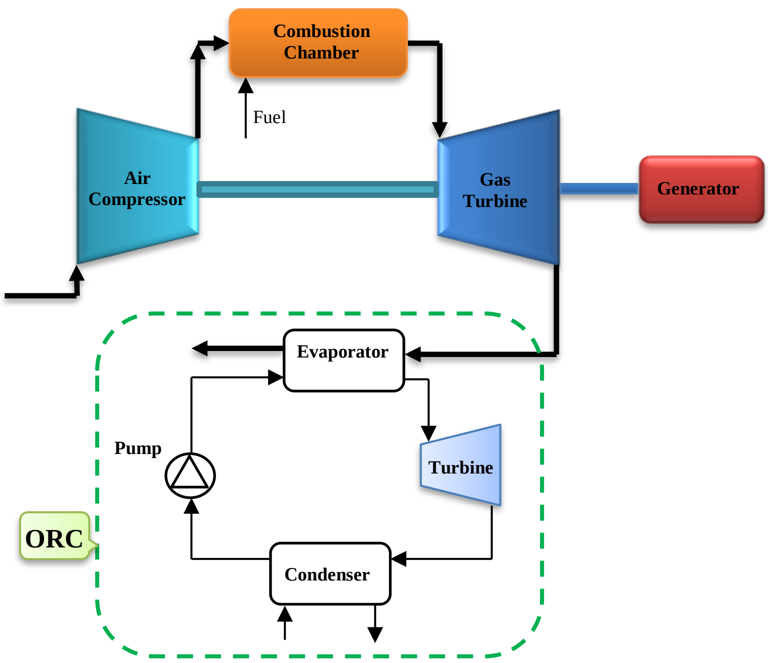


Figure 2: Scheme of ORC installation to recover waste heat from CHP

Table 1: Input parameters to ORC obtained from the sample CHP exhaust

Exhaust gas temperature at full load (°C)	Recoverable temperature for ORC (°C)	$T_{Cooling\ air}$ (°C)	Condensation Pressure (bar)
427	180	15	1

2.2. Cooling systems

As for cooling systems, the air cooled condenser and adiabatic cooler are investigated in this study. Parametric studies are performed on the models of the different cooling systems to find their effect on the cooler performance. Adiabatic cooler in this study is suggested as the combination of pre-cooling pads and air cooler. Figure 3 depicts a schematic of each type of cooler.

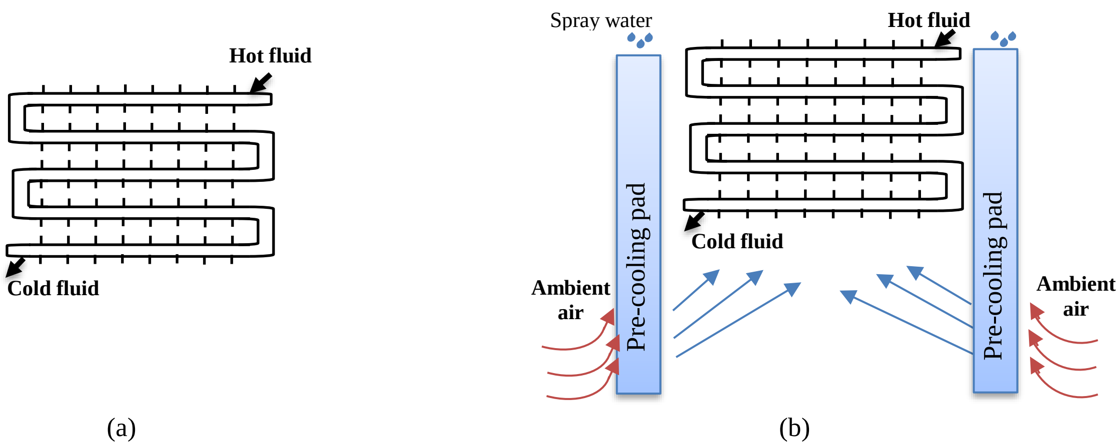


Figure 3: Schematic of a) Dry air cooler, b) Adiabatic cooler

3. Results and discussion

3.1. Performance of ORC

The results of the studied ORC model are available in table 2. Thermal efficiency which is proportion of net generated power to intake duty (Rajabloo, Iora et al. 2016) is 12.7% for this cycle. Although the on-site efficiency will be less due to pressure drops and non-ideal working conditions, results show that waste heat recovery through combining of ORC and the CHP is technically feasible.

Table 2: Results of the ORC plant

Evaporation pressure (bar)	Mas flow rate of working fluid (kg/s)	$Q_{Evaporator}$ (kW)	Net power (kW)	Thermal efficiency %
10	5.5	484.5	61.5	12.7

3.2. Performance of dry air cooler

A dimensional analysis of dry air cooler as an individual component was carried out and the effect of ambient temperature on its performance was investigated. Figure 4 shows the results of this parametric study.

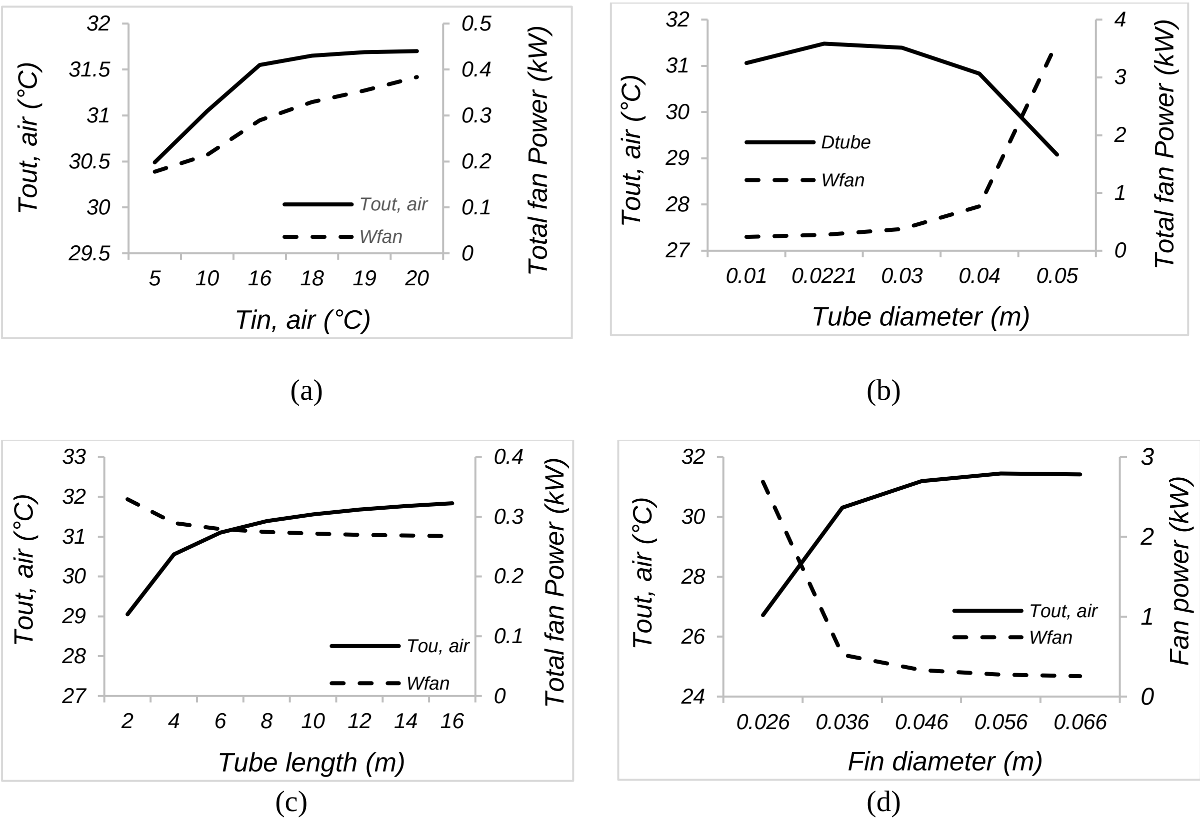


Figure 4: Effect of a) ambient temperature, b) tube diameters, c) tube length, and, d) fin diameter on fan power consumption and temperature of outlet air in the case of a dry air cooler

As the results show, higher ambient temperature results in higher fan power consumption. The higher outlet air temperature, the higher rate of heat exchange between working fluid and air is. As figure 4a depicts the rate of temperature increment of the outlet air from air cooler is less when ambient temperature increases more than 16 °C, and, it results in higher rates of fan power consumption.

Besides, the curve of air outlet temperature becomes almost flat, at temperature close to 20 °C. Above this temperature, required air mass flow rate and consequently air cooler area increases dramatically which is not conceivable to implement in a real plant. Hence, this air cooler is not a supposable option for hot climates with temperatures higher than 20 °C. Therefore, precooling of ambient air to have an adiabatic cooler is suggested and investigated in this study.

Furthermore, increment of the tube diameter (TD) leads to higher fan power and for TD > 0.04 m the increase becomes significant. Also, outlet air temperature decreases at TD > 0.04 m which is not favorable. This is due to increment of hot fluid mass flow rate and the less contact time for heat exchange. Hence tube diameters above 0.04 m are not beneficial.

In addition, increasing length of air cooler tubes leads to a higher air outlet temperature, but, less fan power consumption. This effect becomes, almost flat at tube length of 16 m. Therefore, the optimal tube length is 16 m. The height of the fins, which is indicated as fin diameter, has a similar effect as the tube length on the outlet temperature. For fin diameters above 0.056 m, the line is flat which indicates the optimum fin diameter at 0.056 m.

3.3. Performance of adiabatic cooler

As for the adiabatic cooler, ambient air temperature decreases passing wet pads. This decrement of air temperature for the selected cooling pads are shown at figure 5.

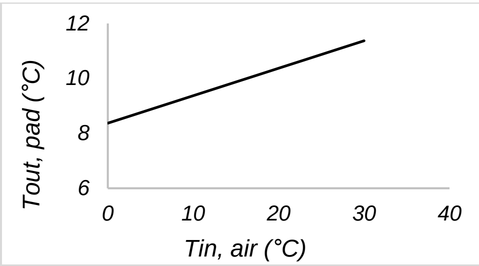
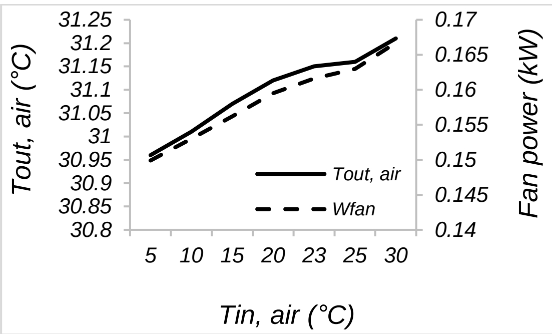
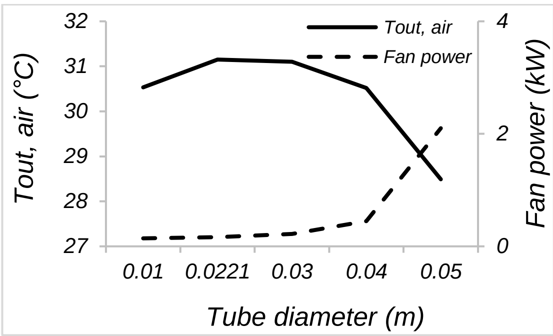


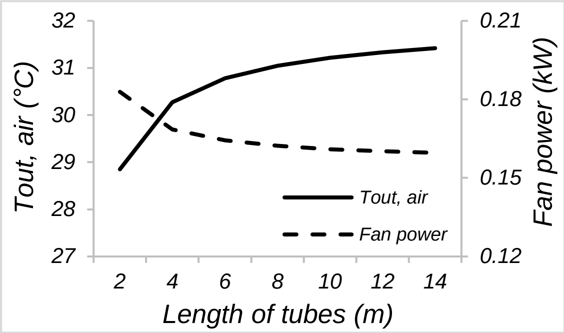
Figure 5: Temperature of air after passing cooling pad regarding ambient temperature at mean ambient humidity of 80%.



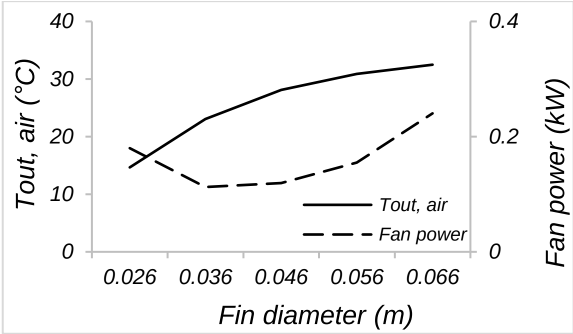
(a)



(b)



(c)



(d)

Figure 6: Effect of a) ambient temperature, b) tube diameters, c) tube length, and, d) fin diameter on fan power consumption and temperature of outlet air in the case of adiabatic cooler

In general, the adiabatic cooler's fan power consumption and outlet air temperature follow the same trend as the dry air cooler except for the fin diameter. By increasing the height of the fins, fan power consumption decreases first, then, it increases again. As figure 6d depicts, a fin diameter of 0.036 m is optimal for this case.

Generally, fan power consumption is less in the case of adiabatic coolers comparing to the dry air cooler. In fact, decrement of air temperature passing pre-cooling pads at adiabatic coolers results in higher driving force for heat exchange rate (providing higher temperature difference). Hence, the system can work at higher ambient temperatures.

Besides, pre-cooling of air at adiabatic cooler is more effective at lower air humidity, and, it is not applicable at 100% humid air.

As figure 6a depicts, the increment rate of outlet air temperature decreases after reaching ambient temperature of 22 °C and it goes through a transition around 24 °C. Having results from dry air cooler, (section 3.2), adiabatic cooler is a good solution for ambient temperatures above 16 °C; and, it is required to have adiabatic cooler for ambient temperatures above 16 °C.

4. Conclusion

In this work the viability of combining ORC with an already installed CHP was investigated thermodynamically. Waste heat data was gathered and used as input into the ORC and cooler models. Moreover, two different cooling systems were investigated at this study. Results showed that capturing waste heat from CHP and implementing it as a heat source for an ORC is thermodynamically viable in the Flemish climate. Moreover, a parametric exploration on dry and adiabatic coolers is carried out. The outcomes demonstrate the effect of air cooler dimensions on the fan power consumption. In addition, the simulations show that for ambient temperatures above 16 °C, dry air coolers are not applicable while adiabatic cooling is the suitable alternative.

NOMENCLATURE

D	Tube diameter	(m)
in	Inlet value	(-)
out	Outlet value	(-)
Q	Heat duty	(kW)
T	Temperature	(°C)

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