Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 158 (2019) 2354–2359

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Technoeconomic analysis of internal combustion engine – organic Rankine cycle cogeneration systems in energy-intensive buildings

Michael C. Simpson, Maria Anna Chatzopoulou*, Oyeniyi A. Oyewunmi, Christos N. Markides

Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, U.K.

Abstract

Organic Rankine cycle (ORC) systems are a promising technology for converting heat to useful power, especially in combined heat and power (CHP) applications with significant quantities of surplus heat that would otherwise be wasted. Beyond the technical performance of these systems, their economic feasibility is crucially important for their wider deployment. In this study, a technoeconomic optimisation of CHP systems is performed in which ORC engines convert heat recovered from internal combustion engines (ICEs), and specifically from both the ICE hot-water output and exhaust-gas stream. The overall aim is to evaluate the impact of the ORC power output and of the components' design and capital cost on the financial viability of a relevant project, while evaluating a range of candidate working fluids. Results indicate that ORC designs optimised for maximum power output correspond to higher specific investment cost (SIC), with the best performing fluids achieving a SIC of £2100 per kW. In contrast, optimisation for minimum SIC returns values as low as £1700 per kW, or 20% lower. For systems designed and optimised for maximum power, a large fraction of jacket water heat is recovered, while for minimum SIC the utilisation drops to minimise the size and cost of the heat exchangers. The best-performing ORC designs for minimum SIC have discounted payback periods (DPPs) of 4 – 5 years, while those optimised for power output have DPPs of 6 – 7 years, however, the net present values (NPVs) of the latter designs are up to 27% higher than the former. Therefore, there is a trade-off to consider over the project life between high-capacity ORC engines with a high SIC and longer DPP, and designs with minimal SIC but lower power output, shorter DPP and lower NPV. The effect of increasing the amount of hot water required by the building is also analysed, and the ORC engine is shown to be sensitive to this factor for some working fluids.

Keywords: CHP; combined heat and power; cogeneration; high efficiency; ORC; organic Rankine cycle; technoeconomic

---

* Corresponding author. Tel.: +44 (0)20 759 41601.
E-mail address: maria-anna.chatzopoulou11@imperial.ac.uk

10.1016/j.egypro.2019.01.283

1. Introduction

Interest in distributed combined heat and power (CHP) generation has been steadily growing, due to the higher overall efficiency of such systems relative to the separate provision of heat and power [1] . This allows a lower overall energy consumption and lower costs for the user, as well as a lower environmental impact by the system compared to traditional heating and centralised power generation systems, which has led many energy-intensive users to consider the adoption of cogeneration systems. A case in point is large supermarket chains, which have high electricity demands for refrigeration. Typical small-to-medium scale CHP systems consist of an internal combustion engine (ICE) coupled with a generator for electricity production. The key to maximising the CHP system performance is to utilise both the power and thermal output from the ICE. In applications where the heat demand is low, or varies significantly over the year, the CHP thermal output is not fully utilised, reducing the overall system efficiency and increasing the payback period.

Organic Rankine cycle (ORC) engines are an effective means of utilising renewable or waste heat at lower temperatures and/or smaller scales compared to conventional power generation in order to generate power [2]. There is a broad literature on studies aiming to optimise ORC thermodynamic performance for a range of heat sources including, among others, solar-driven ORCs [3–5], geothermal applications [6] and waste-heat recovery [7], while the use of computer-aided molecular design (CAMD) approaches based on statistical associating fluid theory (SAFT) have also been shown to lead to suggestions for improved ORC performance [8–10]. While thermodynamic optimisation and technical feasibility are at the core of the development of ORC systems, a critical factor for their wider deployment is their capital expenditure (CAPEX), and operating and maintenance (O&M) costs. The amount of literature publicly available on actual ORC systems costs is limited. In the absence of actual project cost data, obtaining credible estimates of the ORC system cost requires correct sizing and costing of the individual system components. These estimates form the basis of the cost calculations to be undertaken when evaluating the financial viability of ORC engines' deployment. Lecompte et al. [11] optimised an ORC system for minimum specific investment cost (SIC) while recovering heat from the jacket water circuit of a CHP engine. For the system costing, the authors used cost correlations based on actual component prices in the Belgian market. Depending on the working fluid and the heat source conditions, the SIC of the ORC engine varied between £2450 – 2600 per kW. A technoeconomic analysis of a transcritical dual loop ORC recovering heat from ICE was also performed by Yu et al. [12]. The authors used the module costing technique for the equipment costing as provided in Ref. [13]. Results indicate that discounted payback period (DPP) for the ORC engine vary between 7 – 15 years, depending on the working fluid and pressure levels in the system. Braimakis et al. [14] reported SICs for high temperature waste heat recovery of £900 – 3000 per kW, using the cost correlations in Ref. [15].

This work focuses on the technoeconomic optimisation of high-temperature ORC engines, suitable for use in CHP applications when recovering heat recovered by ICEs. Previous studies have assessed the thermodynamic performance of systems using heat from both jacket water and exhaust gases, and this study introduces the economic merits of jacket-water preheating under different heat-demand scenarios. The aim of the study is twofold: i) to investigate how different working fluids affect the ORC output for a given system configuration, when optimising for power or for minimum SIC; and ii) to evaluate the trade-offs between using the jacket water for heating or additional power generation from the ORC engine over the life of a project. This allows us to identify how decisions about the ORC system design and sizing influence the overall financial viability of the project, accounting for both the investment and running costs of the system. The design tool developed can be used to assess the attractiveness of the chosen cycle architecture and operating strategies early in the design process for a CHP-ORC installation, while the generality of the building model means that it is readily adapted to a variety of applications.

2. Methodology

2.1. Organic Rankine cycle (ORC) model

The ORC engine investigated in this work is designed to recover heat from three stationary CHP-ICE engines, designated by the manufacturer as: E250, E375 and E500, where the number gives the approximate electrical output of the ICE in kilowatts. The heat available from the jacket water and exhaust gas for each engine were obtained from the manufacturer's datasheets [16]. The engines are assumed to run at full-load, reflecting a building electrical demand that always exceeds the engines' electrical output. Further, the ORC configuration was chosen to suit an application where the electrical demand significantly exceeds the thermal demand, and thus the potential exists to convert excess heat into electricity. The ORC engine therefore takes heat directly from the exhaust gas stream and also uses a proportion of the hot water (HW) for preheating. This configuration allows (partial) heat recovery from both streams, while using the exhaust gas to heat the working fluid to high temperatures. The heat taken from the water is allowed to vary according to the cycle optimisation for each working fluid.

An ORC model was developed in MATLAB and an optimisation carried out according to the methodology in Ref. [6], extending the work of Vaja and Gambarotta [17]. A counter-flow tube-in-tube heat exchanger (HEX) design was selected for the evaporator and the condenser units. For the single-phase zone, and flow in tubes, the Dittus-Boelter correlation has been used. The Nusselt number modelling equations for the two-phase zone in the evaporator and the condenser are detailed in Chatzopoulou et al. [18,19]. Another important factor for the design of HEXs is the pressure drop experienced by the working fluids. In direct-fired evaporators recovering heat from ICEs exhaust-gas stream, the evaporator HEX design should minimise the additional backpressure added to the engine. In this work, the correlation presented in Ref. [18] for pressure drop for flows in tubes has been used. The efficiency of the pump was set to 65%, while that of the expander was assumed to be fixed at 70% for this study, but will be investigated in more detail in subsequent work.

2.2. System costing

The cost correlations used in this study were obtained by collating manufacturers' technical datasheets and price lists for the key system components. The evaporator and condenser unit correlations were based on materials and assembly cost for stainless-steel HEX obtained from Refs. [20,21]. To obtain the piston-expander unit cost, the cost of piston compressors for refrigeration was used as a first point of reference, as provided in Ref. [22]. The cost correlation provided by Seider et al. [23] was used for the centrifugal pump. The costs are converted into present values using the Chemical Engineering Plant Cost Index (CEPCI). In addition to the hardware costs, a few other cost components are required to estimate total project capital expenditure. These include site preparation, service facilities, contingencies and startup costs in line with Guthrie [13], resulting in a total project CAPEX 30% greater than the capital expenditure on hardware alone.

2.3. Application parameters and financial metrics

The following assumptions were made to model the ORC project economics, taking into account the building demand for heat and power. The CHP-ICE is assumed to run at design (full-load) conditions for 85% of the year, corresponding to a steady demand for baseload electricity from the building or process. During the rest of the year the CHP-ICE is assumed to be inactive. When the CHP-ICE is active heat can be made available to the ORC engine.

Table 1. Assumptions used to estimate financial metrics and cost of hot water from back-up boiler.

Parameter	Value	Parameter	Value
Discount rate [%]	6.0	OPEX [% of CAPEX]	5.0
Electricity price [£/kWh]	0.07	Load factor [%]	85
Gas price [£/kWh]	0.03	Percentage of year with full hot water demand [%]	7.5
Project duration [years]	20		

The merits of each ORC engine and working fluid combination were assessed using multiple metrics. The primary metric is discounted payback period (DPP), commonly chosen for its simplicity and ease of use. DPP measures the time taken to repay the initial investment, taking into account the time value of money by discounting future cash flows. Net present value (NPV) and internal rates of return (IRR) were also calculated, according to the standard formulations.

A stylised model is used to account for the building demand for hot water over the course of a year. In this model, the building requires the full amount of hot water for a given fraction of the year, and at all other times there is excess hot water and the ORC engine is able to extract the optimal amount without penalty. The building hot water demand is therefore aggregated into a single parameter. Three scenarios are considered during CHP-ICE operation (85% of the year):

a) In the 'No HW cost' case, there is no cost associated with using the optimal amount of jacket water for the ORC, corresponding to minimal heating demand from the building.

b) In the ‘Replace HW’ case, the hot water used by the ORC engine has to be replaced using a backup boiler during periods of high thermal demand, and so the cost of natural gas to run the boiler is incurred. For the rest of the year, when the building thermal demand is lower, the jacket water heat can be used without cost.

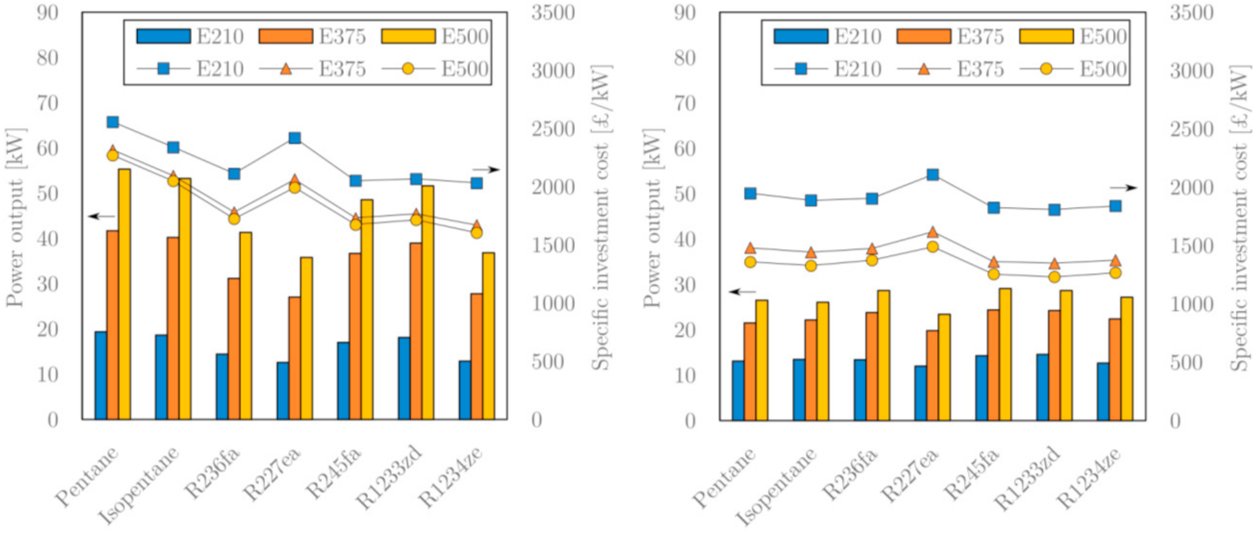
c) In the ‘Bypass ORC/ORC off’ case, the hot water bypasses the ORC engine to supply the building during periods of high thermal demand, and during this time the ORC engine is turned-off and remains inactive. For the remaining time, the jacket water heat can be used without cost.

Evidently, there is scope to increase the fidelity of this model by assessing time-varying heating demand for a particular building and implementing optimal operational strategies for the ORC engine. However, the present model allows a preliminary study of the effect of building thermal demand on the project’s profitability.

3. Results and discussion

3.1. Technoeconomic optimisation results

The net output power from the ORC engine and the SIC of the installation are shown in Fig. 1 (a) and (b), optimised for maximum power and minimum SIC, respectively. All of the hot water is considered to be available for ORC engine use, though most optimal designs use less than half. Pentane is seen to deliver the highest power output, but also has the highest SIC when power is maximised. For the E500 engine with pentane, the ORC engine achieves a net efficiency of 14.4% due to the high temperature of the exhaust gas. The maximum amount of heat is extracted from the exhaust gas, as well as 33% of the jacket water heat, in order to achieve an output power of 55 kW.



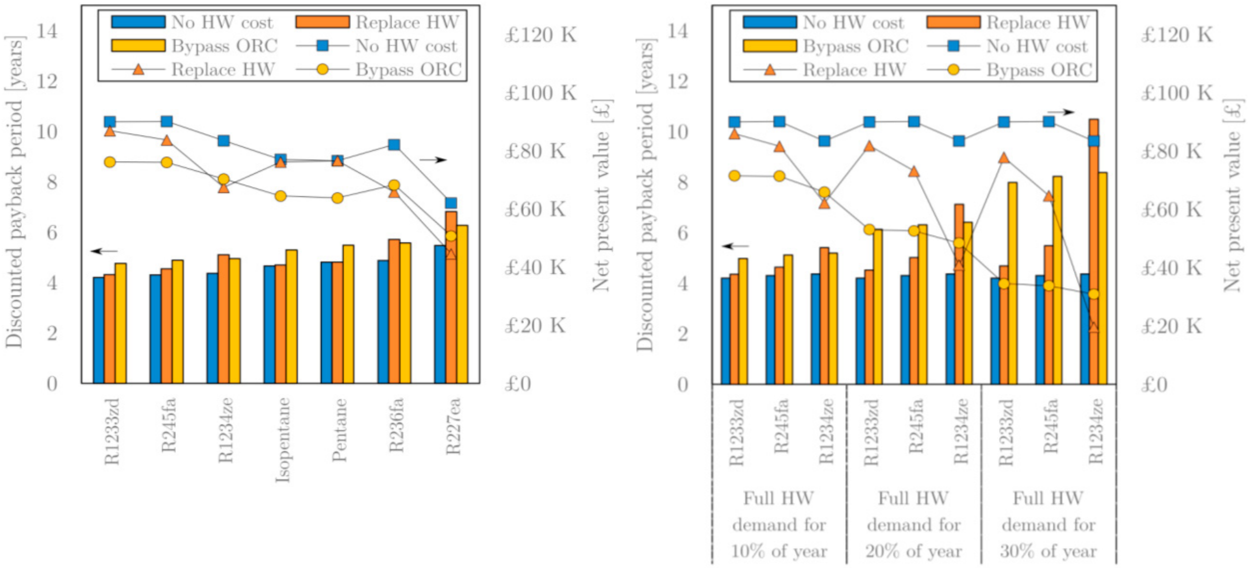
(a) (b)

Fig. 1. ORC power output and installed SIC by working fluid for each CHP-ICE, optimised for: a) maximum power output, and b) minimum SIC.

When optimising for minimum SIC, the ORC engine power output for all ICEs and working fluids reduces sharply, and the differences between the fluids become less pronounced. The minimum SIC for each ICE is achieved by selecting R1233zd, a low global-warming potential (GWP) fluid, although R1234ze and the higher-GWP R245fa perform similarly well. It is worth noting, however, that these fluids use different quantities of hot water to achieve comparable power and cost performance. In both optimisations, the minimum SIC is observed for the ORC system for the largest engine, the E500. This is a consequence of the economies of scale afforded by larger components. The ORC system for the E210 engine has a markedly higher SIC because a greater proportion of the heat from this CHP engine is delivered in the form of hot water (226 kW) rather than exhaust gas (110 kW). The power- and cost-optimal ORC system designs for the E210 engine fully exploit the exhaust gas heat, which limits the amount of the heat that can be extracted from the hot water.

3.2. Financial metrics evaluation

Figure 2 (a) shows a summary of the financial metrics for an ORC project with the E500 engine. All three scenarios for hot-water usage during periods of high building thermal demand are shown, in which the hot water is either used without penalty, replaced by burning natural gas, or the ORC engine is bypassed. In each case, the ORC engine is optimised for minimum SIC, as this gives a lower DPP. In all scenarios, DPPs of 4 – 5 years are obtainable for the best working fluids. Minimising the SIC does not necessarily produce the highest NPV, which can favour a higher initial investment to achieve greater returns later on. For several working fluids, including R1233zd, the NPV is greater when power is maximised rather than SIC minimised (not shown here), by up to 27%. This finding, noted for the E375 and E500 engines, is most striking when there is no cost for using hot water. Figure 2 (b) shows the effect of increasing the proportion of the year for which all of the hot water is needed by the building. In the ‘Replace HW’ scenario, the cost of natural gas to replace the hot water has a relatively minor influence for R1233zd, which uses only 7% of the hot water to perform optimally. However, increasing the period of full hot water demand to 30% seriously affects the profitability of the R1234ze system, which uses 37% of the available hot water. At this point the DPP reaches 10.5 years, and for this fluid it is preferable to bypass the ORC engine and supply the building from the CHP instead.



(a) (b)

Fig. 2. Discounted payback period (bars) and net present value (lines) for the three different hot water scenarios for: (a) all working fluids modelled, and (b) for the three best working fluids, under the assumption of all jacket water heat being required for 10 – 30% of the year. The ORC system was designed for the E500 CHP engine (500 kW electrical output) and optimised for minimum SIC.

4. Summary and conclusions

An ORC engine architecture that uses hot water and exhaust gas in sequence from a CHP-ICE to preheat and evaporate the working fluid has been analysed and optimised to either maximise power output or minimise SIC. Results indicate that higher power-output designs tend to have higher SICs for the ORC engine, with pentane delivering 55 kW of power at an SIC of £2100 per kW for the E500 engine. Optimisation for minimum SIC, on the other hand, returns SIC values as low as £1700 per kW, or 20% lower, with refrigerants such as R1233zd performing well. Consequently, there is a trade-off to consider over the lifetime of the project between selecting ORC engines with high-rated capacities but high investment costs, and designs with minimised SICs but lower power outputs. Furthermore, the design with the minimum SIC can differ from that with the maximum NPV, with designs for maximum power output offering up to 27% higher NPV than designs for minimum SIC. For systems that maximise power, a high fraction of jacket water heat is recovered, while for minimised SIC the utilisation drops, reducing the cost of the heat exchangers. It emerges that the profitability of the chosen architecture, while capable of achieving high efficiency and good utilisation of the available heat streams, can be highly sensitive to the hot-water demand for the application. Where low heat-to-power demands exist, for example in warm climates or for electricity-intensive buildings and processes, this architecture can be attractive, with DPPs for some systems around 4 – 5 years. However, where all the hot water of the ICE jacket water circuit may be required by the building for part of the year, care must be taken to select the working fluid and operating strategy accordingly. The design tool developed here can be used to ensure that such choices are made appropriately.

Acknowledgements

This work was supported by the UK Engineering and Physical Sciences Research Council [grant no. EP/P004709/1 and award number 1855813]. The authors would also like to thank the Imperial College President's PhD Scholarship Scheme, and the Climate-KIC PhD Added Programme for funding this research. Data supporting this publication can be obtained on request from cep-lab@imperial.ac.uk.

References

[1] Markides CN. The role of pumped and waste heat technologies in a high-efficiency sustainable energy future for the UK. Appl Therm Eng 2013;53:197–209. doi:10.1016/j.applthermaleng.2012.02.037.

[2] Markides CN. Low-concentration solar-power systems based on organic Rankine cycles for distributed-scale applications: Overview and further developments. Front Energy Res 2015;3:1–16. doi:10.3389/fenrg.2015.00047.

[3] Freeman J, Hellgardt K, Markides CN. An assessment of solar-powered organic Rankine cycle systems for combined heating and power in UK domestic applications. Appl Energy 2015;138:605–20. doi:10.1016/j.apenergy.2014.10.035.

[4] Freeman J, Hellgardt K, Markides CN. Working fluid selection and electrical performance optimisation of a domestic solar-ORC combined heat and power system for year-round operation in the UK. Appl Energy 2017;186:291–303. doi:10.1016/j.apenergy.2016.04.041.

[5] Freeman J, Guarracino I, Kalogirou SA, Markides CN. A small-scale solar organic Rankine cycle combined heat and power system with integrated thermal energy storage. Appl Therm Eng 2017;127:1543–54. doi:10.1016/j.applthermaleng.2017.07.163.

[6] Oyewunmi OA, Markides CN. Thermo-economic and heat transfer optimization of working-fluid mixtures in a low-temperature organic Rankine cycle system. Energies 2016;9:1–21. doi:10.3390/en9060448.

[7] Maraver D, Royo J, Lemort V, Quoilin S. Systematic optimization of subcritical and transcritical organic Rankine cycles (ORCs) constrained by technical parameters in multiple applications. Appl Energy 2014;117:11–29. doi:10.1016/j.apenergy.2013.11.076.

[8] Lampe M, Groß J, Bardow A. Simultaneous process and working fluid optimisation for Organic Rankine Cycles (ORC) using PC-SAFT. Comput Aided Chem Eng 2012;30:572–6. doi:10.1016/B978-0-444-59519-5.50115-5.

[9] White MT, Oyewunmi OA, Haslam AJ, Markides CN. Industrial waste-heat recovery through integrated computer-aided working-fluid and ORC system optimisation using SAFT-γ Mie. Energy Convers Manag 2017;150:851–69. doi:10.1016/j.enconman.2017.03.048.

[10] Oyewunmi OA, Taleb AI, Haslam AJ, Markides CN. On the use of SAFT-VR Mie for assessing large-glide fluorocarbon working-fluid mixtures in organic Rankine cycles. Appl Energy 2016;163:263–82. doi:10.1016/j.apenergy.2015.10.040.

[11] Lecompte S, Huisseune H, van den Broek M, De Schampheleire S, De Paepe M. Part load based thermo-economic optimization of the organic Rankine cycle (ORC) applied to a combined heat and power (CHP) system. Appl Energy 2013;111:871–81. doi:10.1016/j.apenergy.2013.06.043.

[12] Shu G, Yu G, Tian H, Wei H, Liang X, Huang Z. Multi-approach evaluations of a cascade-organic Rankine cycle (C-ORC) system driven by diesel engine waste heat: Part A – Thermodynamic evaluations. Energy Convers Manag 2016;108:579–95. doi:10.1016/j.enconman.2015.10.084.

[13] Turton R, Bailie RC, Whiting WB, Shaelwitz JA. Analysis, synthesis and design of chemical processes. 3rd Ed, Pearson Education, 2009. doi:10.1017/CBO9781107415324.004.

[14] Braimakis K, Karellas S. Integrated thermoeconomic optimization of standard and regenerative ORC for different heat source types and capacities. Energy 2017. doi:10.1016/j.energy.2017.01.042.

[15] Peters MS, Timmerhaus KD, West RE. Plant design and economics for chemical engineers. 5th Ed, McGraw-Hill, 2004.

[16] Ener-G. Ener-G cogeneration 2016. www.energ-group.com/combined-heat-and-power/cogeneration (accessed 18 Feb. 2018).

[17] Vaja I, Gambarotta A. Internal Combustion Engine (ICE) bottoming with organic Rankine cycles (ORCs). Energy 2010;35:1084–93. doi:10.1016/j.energy.2009.06.001.

[18] Chatzopoulou MA, Simpson M, Markides CN. Off-design optimisation of medium-scale organic Rankine cycle with piston expander for combined heat and power applications. Appl Energy 2018; in preparation.

[19] Chatzopoulou MA, Markides CN. Advancements in organic Rankine cycle system optimisation for combined heat and power applications: Components sizing and thermoeconomic considerations. Proc 30th Int Conf Effic Cost Optim Simul Environ Impact Energy Syst, San Diego, 2017.

[20] Daccord R. Cost to benefit ratio of an exhaust heat recovery system on a long haul truck. Energy Procedia 2017;129:740–5. doi:10.1016/j.egypro.2017.09.108.

[21] Alfa Laval. Pricelist refrigeration equipment – 2016. www.aotech.cz/UploadFiles/Doc/Refrigeration%20PPL-EN%202016-01-01.pdf (accessed 28 July 2018).

[22] AREA. AREA product catalogue - 2017. www.areacooling.co.uk/?download=true#otro (accessed 18 Feb. 2018).

[23] Seider WD, Lewin DR, Seader JD, Widagdo S, Gani R, Ming NG K. Product and process design principles: Synthesis, analysis and evaluation. 4th Ed, Wiley, 2017.