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Process Integration for Power-dominated Cryogenic Energy Systems

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An overview of complex design problems imposed in power-dominated low-temperature processes will be given, together with explanation about how Process Integration techniques can be successfully applied in enhancing energy efficiency and improving economic performance. Design methodology with the developed optimisation frameworks will be addressed with an industrial case study in natural gas processing.

1. Introduction

The energy systems which provide a large amount of refrigeration for the cooling of process streams are power-dominated, due to heavy compression duties required for refrigeration cycles, and it is important to select the most appropriate drivers and to design their arrangement. Determining optimal configuration of drivers is not straightforward, as decision-making in power systems involves consideration of various available drivers as well as its thermodynamic, environmental and economic implications. This drivers selection is a part of design problem of site utility systems, and therefore, the optimisation framework should allow thorough investigation of system interactions between selection of drivers, and mechanisms for energy generation and distribution, and investigate synergetic benefits from integrating power systems in the context of utility systems.

The design of refrigeration cycle is itself also challenging when cooling is needed for a large temperature range, because there existed a large number of design options, including multi-level cooling, cascaded cycles, and mixed refrigeration cycles. The overall energy systems will be heavily dependant on the decision made on the design of refrigeration cycle, and the design methodology should integrate systematically between power systems (driver selections), refrigeration cycles and site utility systems in a holistic way.

2. Multi-period Synthesis of Power Systems

The selection of drivers for power-dominated processes is very complex because a number of options are available and consequently its decision is highly combinatorial. Direct drive gas turbine, steam turbine or electric motor can be applied to meet major mechanical demands, and the number and size of this equipment should be optimised, together with network configuration, to minimize capital and operating costs of energy systems. Gas turbine has been widely used either direct driver or power generation in

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process industries. It is important to consider ambient conditions in the conceptual design stage when gas turbines are introduced, as the performance of gas turbine is heavily dependent on ambient conditions (Figure 1). As ambient conditions are not the same throughout the year and engineering margin is typically used in the design stage, the gas turbine is not always operated at the full load and the power output is not at the same level. When the gas turbine is operated at the part load, the energy efficiency is decreased, which should be also considered in the design.

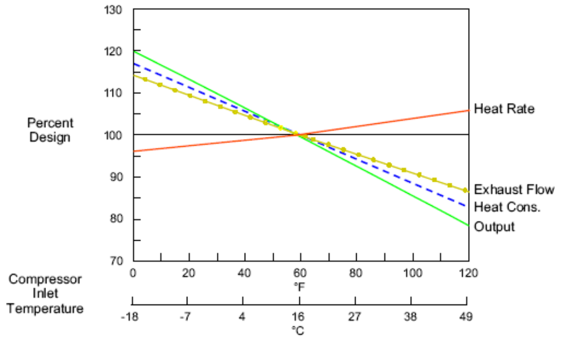

Figure 1. Gas turbine performance variations against ambient temperature (Brooks, 2000)

Del Nogal *et al*. (2010a, 2010b) proposed the optimisation for drivers selection which identifies cost-effective matching between available drivers options and mechanical demands. Their method did not consider part-load performance of gas turbines. In order to accommodate ambient conditions and part-load performance, the multi-period optimisation method has been proposed, and ambient conditions are defined for each period. The superstructure approach is used to find the most appropriate type, number, size and configurational arrangement of drivers for the given number of mechanical demands and available driver options, subject to economic criteria and practical constraints. Superstructure is arranged such that one driver can provide mechanical power for single demand or more than two demands which share the same shaft, and also discrete nature of direct drive gas turbine is systematically considered, together with help motors and generators.

The case study has been carried out with two geographical regions, to demonstrate the concept of design method proposed and to highlight how ambient conditions affect the design and its economics. Power and electricity demand data is given in Table 1, and two optimal results are presented for modest ambient conditions (Region A, Figure 2) and warm ambient conditions (Region B, Figure 3). Gas turbine performance has been estimated for average ambient condition in each period (Region A: ambient temperature range between 5 and 25 ^{o}C; Region A: ambient temperature range between 15 and 35 ^{o}C) and working load in each period is optimized correspondingly. From these two results, although basic demands for mechanical power are the same, the design of power systems and its economics is different. Compared to Region A, a larger power plant is selected in the Region B, due to worse equipment performance deterioration, which will increase fuel consumptions and annualised cost in this design. Performance deterioration of gas turbine is systematically considered in the optimisation, which allows finding better solutions.

Table 1. Case study: power and electricity demand

Mechanical power demand	Compressor	Demand [MW]	Compressor	Demand [MW]
	C1	2.5	M1	57.64
	C2	6.96	M2	18.74
	C3	12.35	M3	27.34
	C4	32.25		
Electricity demand	42.65 MW			

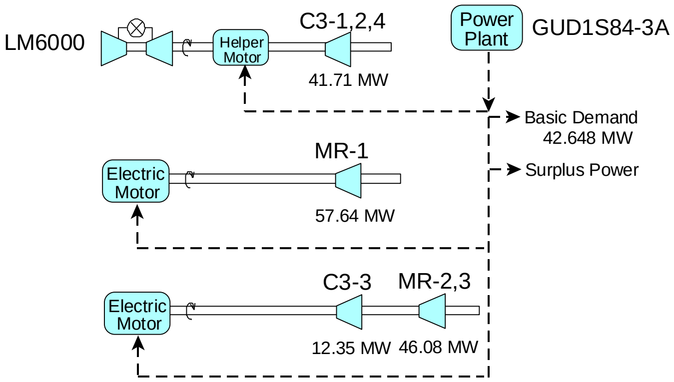

Figure 2. Optimal design of power systems - Region B

3. Design of Mixed Refrigerant Cycles

Refrigeration cycle based on vapour recompression is widely used when operation at low temperature is needed in process industries. Reducing compression duties for refrigeration cycles is very important to improve cost-effectiveness of low-temperature processing, for example, gas processing, natural gas liquefaction, and cryogenic air separation. Various structure options are available for providing the cooling at low temperature, as shown in Figure 4. Multi-level cooling is a typical arrangement for covering wide temperature range, based on either a single cycle or cascaded cycle. The refrigeration cycle can be designed with a mixture of refrigerants, which can maintain the simple structure of cycles. All these available options can be coupled together to satisfy the cooling demand and inadequate integration results in significant increase in shaftpower and capital investment.

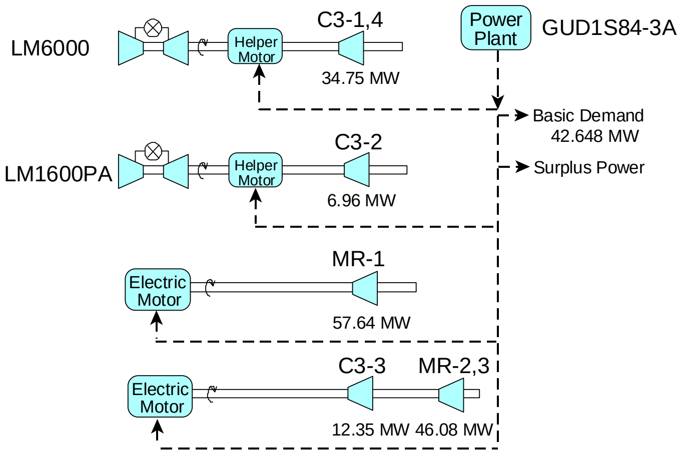

Figure 3. Optimal design of power systems - Region A

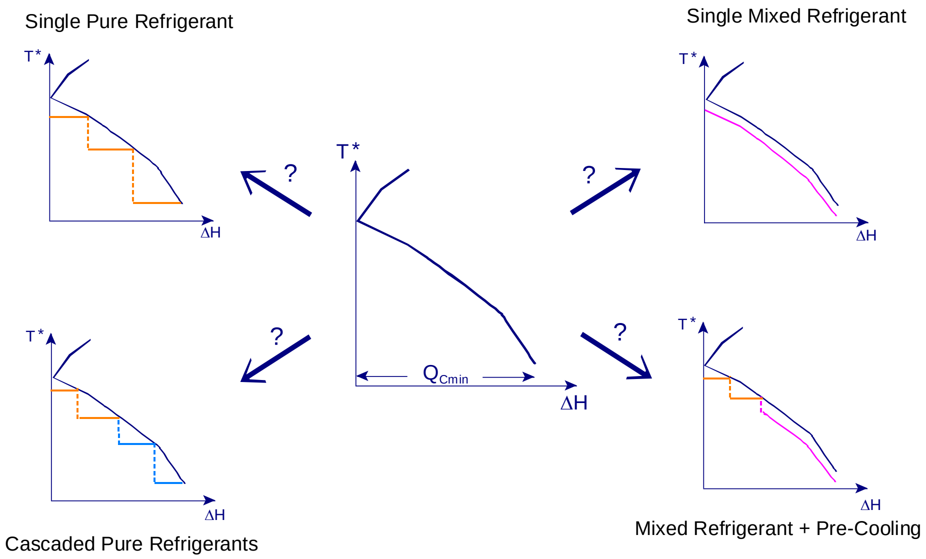

Figure 4. Options for refrigeration cycles (CPI, 2005)

Heat Integration plays a significant role in improving energy efficiency of refrigeration cycles, and flowsheet configuration has a significant impact on the system performance (Friedler, 2009). Especially, when mixed refrigerants cycle is introduced, optimal selection of compositions and operating conditions are essential (Vaidyaraman and Maranas, 2002; Smith, 2005; Gundersen *et al.*, 2009). Therefore, optimisation is needed to screen different structures of cycles systematically and to find optimal operating conditions (i.e. refrigerant flowrate, operating pressure, compositions of mixed refrigerants). Optimisation frameworks developed are based on stochastic techniques using Genetic Algorithm, due to highly non-linear nature of the model, although global optimality is not guaranteed and the computational effort is considerable. The optimiser has been designed to evaluate all the degrees of freedom existed in the design of refrigeration cycles, which are developed by Del Nogal *et al.* (2008). Figure 5 illustrates a typical arrangement of propane (C3) pre-cooled mixed refrigeration cycles, which is widely used in natural gas processing. Simulation model has been built to carry out mass and energy balances, heat integration for heat exchange, calculation for expansion and multi-stage compression.

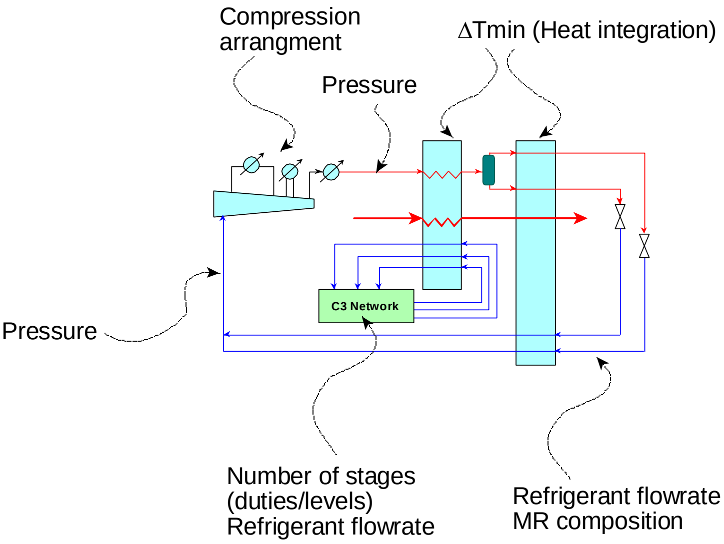

Figure 5. Design options in the design of refrigeration cycles

In Figure 5, three or four levels of propane refrigeration cycles (shown as C3 network in Figure 5) are used for cooling of natural gas stream as well as pre-cooling of refrigerant stream before expansion. Mixed refrigerant cycle (outer cycle with two expansion valves in Figure 5) is used for liquefying natural gas to the desired condition. Figure 6 illustrates energy composite curves when the propane pre-cooled mixed refrigeration cycle is optimized, in which close matching between hot composite curve and cold composite curve (i.e. cooling by refrigeration) is obtained through optimisation. The overall cooling demand profile in Figure 6 is combination of cooling for process stream and cooling for the fluid of refrigeration cycle before expansion.

4. Conclusions

This presentation provides an overview of recent developments in the area of design and optimisation of energy systems in low temperature processing. Process Integration techniques, as a system analysis tool, have been applied to investigate energy systems in a holistic way which is able to find economic and realistic design for power systems and refrigeration cycles.

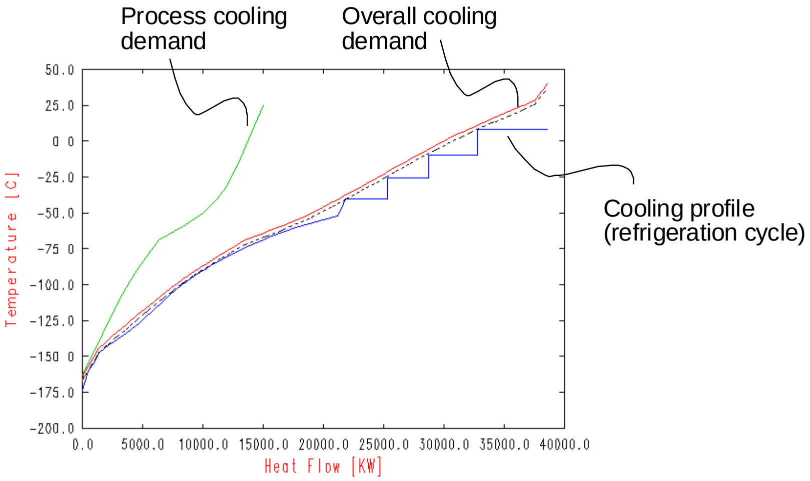

Figure 6. Energy composite curve for the case study

References

Brooks, F.J., 2000, Gas turbine performance characteristics. GE Power Systems, Technical Document GER-3567H, GE

Centre for Process Integration (CPI), 2005, Low Temperature System Design: CPD course, The University of Manchester, Manchester, UK

Del Nogal, F., Kim, J., Perry S. and Smith R., 2010a, Synthesis of mechanical driver and power generation configurations, Part 1: Optimization framework, AIChE Journal, doi: 10.1002/aic.12141

Del Nogal, F., Kim, J., Perry S. and Smith R., 2010b, Synthesis of mechanical driver and power generation configurations, Part 2: LNG applications, AIChE Journal, doi: 10.1002/aic.12142

Del Nogal, F., Kim, J., Perry S. and Smith R., 2008, Optimal Design of Mixed Refrigerant Cycles, Ind. Eng. Chem. Res., 2008, 47 (22), 8724-8740

Friedler, F. 2009, Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, Chemical Engineering Transaction, 18, 1-26

Gundersen T., Berstad D. and Aspelund A., 2009, Extending Pinch Analysis and Process Integration into Pressure and Fluid Phase Considerations, Chemical Engineering Transactions, 18, 33- 38

Smith R., 2005, Chemical Process Design and Integration, John Wiley & Sons, Ltd., UK

Vaidyaraman S. and Maranas C., 2002, Synthesis of Mixed Refrigerant Cascade Cycles, Chemical Engineering Communications, 189 (8), 1057-1078