OPTIMIZATION OF GAS TURBINE USING NLP MODEL

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Abstract

In the simultaneous heat and power integration approach with additional production the optimization problem is formulated using superstructure. Nonlinear programming (NLP) contains equations enabling structural and parametric optimization. In the present work the NLP model is formulated with the optimum energy target of the process integration and generation of electricity using a gas turbine. The reactor is acting as a combustion chamber of the gas turbine plant. The simultaneous NLP approach can account for capital cost, integration of combined heat and power, process modification and additional production trade-offs accurately and can thus yield better solution. The simultaneous NLP gives better results as the other nonsimultaneous methods.

The approach has been illustrated by a complex methanol production process. The objective function has increased the annual profit by 2,59 MEUR/a.

1. Introduction

Heat and power integration can be performed by pinch analysis or by nonlinear programming, NLP. Pinch analysis is guiding heat and power integration using extended grand composite curve (Glavič, 2001). The pinch analysis does not guarantee the global optimal solution because it cannot be used simultaneously with material balances but it quickly proposes good ideas for process heat and power integration of complex processes. Combined heat and power integration adds degrees of freedom to the optimisation method (Maréchal and Kalitventzeff, 1997). The graphical representations of gas turbine using pinch analysis help us to better understand the integration (Maréchal and Kalitventzeff, 1996). A step-wise methodology of gas turbine integration combined with heat and power cogeneration developed by Axelsson and coauthors (2003) is based on pinch analysis.

The NLP algorithm (Biegler et al., 1997), which is based on mathematical programming can be used for rigorous process and power integration. Although simultaneous, it is difficult to converge for complex and energy intensive processes because the number of variables increases with the number of combinations.

In this paper, we are concerned with simultaneous NLP mathematical optimization techniques after including integration of combined heat and power and increased production.

2. Heat and power integration

Heat integration can reduce fuel flow rate, CO_2 and SO_2 emissions and thereby pollution. Heat integration and generation of electricity using a gas turbine is proposed. Then the simultaneous mathematical optimization method is presented, including integration of combined heat and power and increased production. The NLP model contains equations of structural and parametric optimization with process operating constrains (Brooke et al., 1992). NLP can optimize process integration and electric power production.

2.1. Gas turbine system

Usually, a gas turbine operates with internal combustion. Air and fuel pass through a compressor into a combustion chamber. The combustion products are lead through a turbine, which drives an electric generator.

Many chemical products are produced at high pressure and temperature, than separation at lower pressure and temperature follows. This pressure change can be used to drive a turbine compled to a generator of electricity. The reactor is acting as a combustion chamber of gas turbine plant. The turbine uses process gas as a working fluid (Greeff et al., 2002). Gas turbine can be used in the plant with a steady flow rate.

The designed medium pressure of the turbine can be varied. Its power (P_{tur}) is a function of the outlet ($T_{\mathrm{tur,\ out}}$) temperature, molar heat capacity (C_m) and amount flow rate (F; eq. 1). The inlet temperature ($T_{\mathrm{tur,\ in}}$) is constant:

$$P_{\mathrm{tur}} = C_{\mathrm{m}} \cdot (T_{\mathrm{tur,\ in}} - T_{\mathrm{tur,\ out}}) \cdot F \cdot \eta_{\mathrm{tur}} \qquad (1)$$

The efficiency of the medium pressure turbine (η_{tur}) is supposed to be 80 %.

3. Case study

We tested this idea using a complex process of low-pressure Lurgi methanol production. In the present work, we focus on the efficient NLP model formulation which is including all process units in the cycle. The methanol reactor is operated at high pressure and unconverted gas is recycled. The high recycle ratio and operating pressure of the reactor are exploited to produce electricity. The reactor is acting as the combustion chamber of the gas turbine plant, the turbine using process gas as a working fluid. In conventional processes the heat flow rate downstream the reactor is used to integrate the inlet stream with the outlet one without cogeneration. A part of the flow sheet of the methanol plant with gas turbine is shown in Figure 1. The gas turbine (TUR) is placed downstream the reactor. The exothermic reactor (REA) is to be operated at the existing parameters. The inlet stream of the reactor is heated by a process stream (HEPR) or by high pressure steam (HEST) or combined by both of them. The stream is cooled using air (HEA) and water (HEW) heat exchangers before entering the flash (SEP). The liquid stream of the separation is the product and the recycled gas stream is compressed to 51 bar in a two stage compressor (COMP1, 2) with intermediate water cooling (HEW1). The NLP model is optimizing the outlet flow rate of purge gas and additional annual production of methanol in the reactor.

The NLP model is including the equations for heat and mass balance (Kovač Kralj et al., 2000). The additional annual income includes electricity production and additional production of methanol ($\Delta F_{\mathrm{M}} = F_{\mathrm{M}} - 154{,}59$ mol/s; F_{M} being the optimized amount flow rate of methanol and 154,59 mol/s the existing one).

The annual depreciation of the medium pressure turbine ($C_{\mathrm{d,\ tur}}$ in EUR/a) is a function of the power (P_{tur}; Biegler et al., 1997):

$$C_{\mathrm{d,\ tur}} = (22\,946 + 13{,}5 \cdot P_{\mathrm{tur}}) \cdot 2 \qquad (2)$$

The published cost equations for the equipment are usually not adjusted to the real, higher industrial costs, therefore, the costs are multiplied by 2.

In the model the existing areas can be used ($A_{\mathrm{HE,ex}}$), enlarging them with additional areas ($\Delta A_{\mathrm{HE,add}}$) if necessary. The additional annual depreciation of the enlarged and new areas ($A_{\mathrm{HE,new}}$) of heat exchangers (Table 1) is multiplied by the payback multiplier (r = 0,216; Ahmad, 1985) to obtain the maximum annual profit in heat and power integration:

$$\begin{aligned} &\text{Max. additional annual profit} = \\ &C_{\mathrm{el}} \cdot P_{\mathrm{tur}} + C_{\mathrm{M}} \cdot \Delta F_{\mathrm{M}} - C_{37} \cdot \Phi_{\mathrm{HEST}} - (22\,946 + 13{,}5 \cdot P_{\mathrm{tur}}) \cdot 2 \\ &- [2\,605 \cdot P_{\mathrm{COMP1}}^{0{,}82} \cdot 2 - 2\,605 \cdot P_{\mathrm{COMP2}}^{0{,}82} \cdot 2 \\ &- \sum_{\mathrm{new}} (8600 + 670 \cdot A_{\mathrm{HE,\ new}}^{0{,}83}) \cdot 3{,}5 \cdot 2 - \sum_{\mathrm{add}} 670 \cdot \Delta A_{\mathrm{HE,\ add}}^{0{,}83} \cdot 3{,}5 \cdot 2] \cdot r \end{aligned} \qquad (3)$$

new = HEST, HEW1
add = HEW, HEA, HEPR

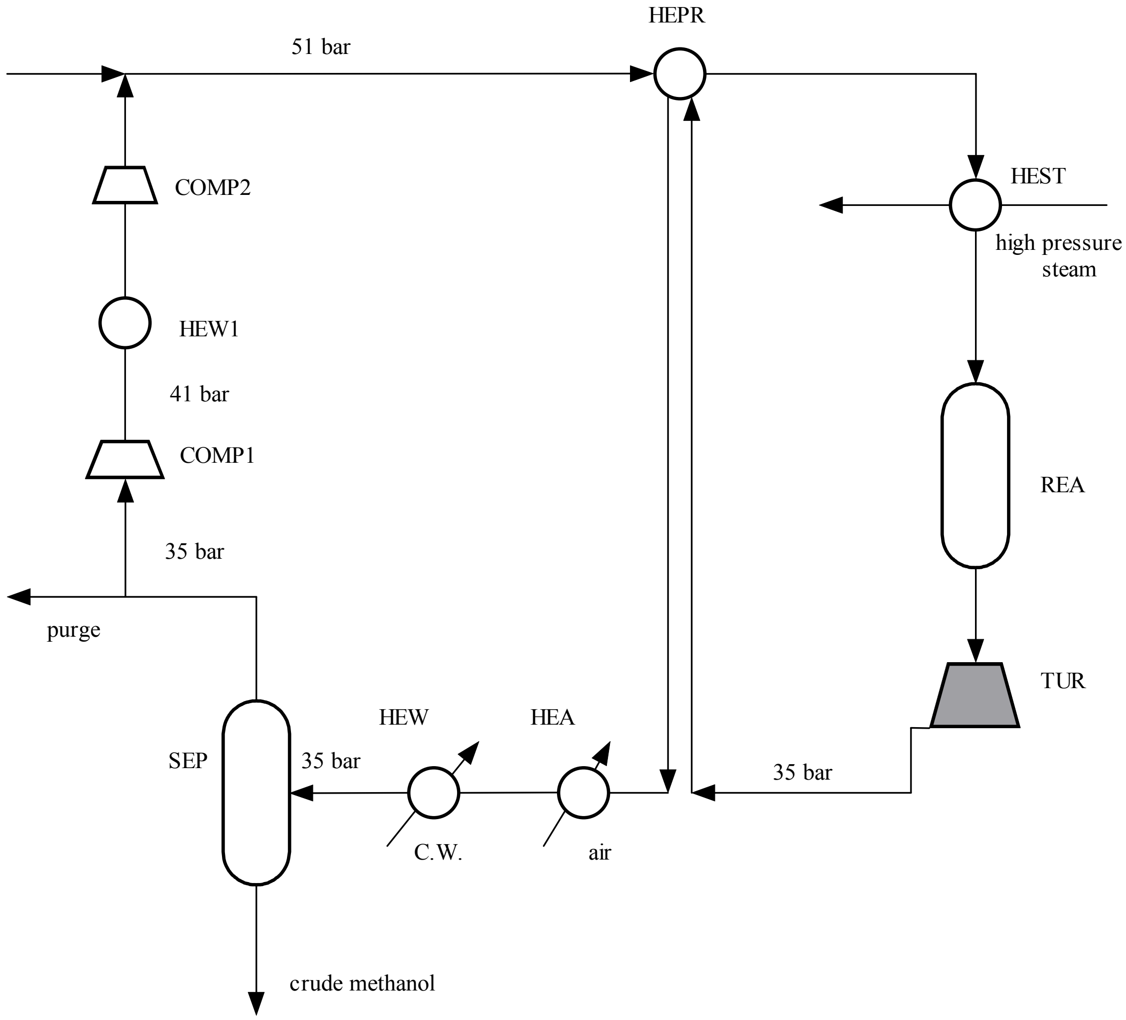

Figure 1: The flow sheet of the methanol plant with gas turbine.

Table 1: Cost data for example process.

Installed cost of heat exchanger [*]/EUR:	$(8\,600{,}0 + 670 \cdot A^{0{,}83}) \cdot 3{,}5 \cdot 2$	
Cost of compressor [&]/EUR:	$(2\,605 \cdot P^{0{,}82}) \cdot 2$	
Cost of displacing one heat exchanger [&]/EUR:	4 000,0	
Cost of methanol (C_M)[+]:	115,0	EUR/t
Cost of electricity (C_{el})[**]:	435,4	EUR/(kW · a)
Cost of 37 bar steam (C_{37})[**]:	106,3	EUR/(kW · a)

* Tjoe and Linnhoff, 1986 A = area in m^2
** Swaney, 1989
& Biegler, 1997; P = power in kW
\+ ten years average

The simultaneous NLP heat and power integration and optimization selected the structure of electricity generation using the gas turbine pressure drop from 49,7 bar to 35 bar with outlet temperature $T_{\mathrm{tur,out}}$ = 100 °C. The structure enables the generation of 15,0 MW of electricity. The steam exchanger (HEST) needs 17,8 MW of heat flow rate. The integrated process streams in HEPR exchange 2,4 MW of heat flow rate. The power of the first and the second compressor is 2,0 MW and 2,8 MW, respectively. The HEW1 exchanges 2,0 MW. In the heat exchangers HEW and HEA

6,9 MW and 5,2 MW of heat flow rate are exchanged by cooling, respectively. The additional annual methanol production is 0,75 mol/s, decreasing purge gas outlet flow rate from 210 mol/s to 190 mol/s.

The additional annual depreciation of the gas turbine, new heat exchangers (HEPR, HEW1) having 550 m^2 and 324 m^2 area, displacement of the existing heat exchangers HEPR to HEST and the new two-stage compressor is 2 117 kEUR/a. The cost of high pressure steam used in HEST is 1 889 kEUR/a. The additional annual income of the electricity produced is 6 525 kEUR/a. The additional annual income of the methanol produced is 79 kEUR/a. The additional profit of the process and power integration is estimated to be 2 590 kEUR/a.

The NLP program is including 111 equations and 120 variables with computation time of 13,46 s.

4. Conclusions

The paper has presented efficient NLP model formulations for simultaneous cogeneration of electricity using gas turbine and process heat integration. The gas turbine can be mounted in the process cycle with high pressure and temperature drop. We have carried out simultaneous heat and power optimization with additional profit of 2,59 MEUR/a.

5. References

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