STEAM PRODUCTION OPTIMIZATION IN A PETROCHEMICAL INDUSTRY

E. G. de Magalhães[1*], K. Wada[2], A.R. Secchi[3]
[1]Process Team – Engineer Unity - COPESUL
[2,3]Group of Integration, Modeling, Simulation, Control and Optimization of Processes (GIMSCOP)
Departamento de Engenharia Química - Universidade Federal do Rio Grande do Sul

Abstract. The rational use of utilities (electric energy, steam, and water) represents nowadays the great challenge to assure the competitiveness and sustainability of industries. The proposed work presents the minimization of the steam generation in a petrochemical company, which has a production of electric energy and steam by co-generation system. In the case study, the steam network is composed by four levels of pressure that supply either thermal (heat exchangers), process (strippers) or power (pumps, compressors and electric energy) demands. The steam is produced in boilers or furnaces only in the highest level of pressure and the lower levels are produced by the extraction of turbines and/or letdown valves. Therefore, there is a balance to achieve between work and heat supply. Actually, this balance is made either by localized control loops or manually by operation people. The optimum configuration, nevertheless, is not trivial and cannot be readily defined by heuristics or localized control loops. The application of an optimization model is proposed in a way that based on the definition of needs of electric energy generation, process loads and steam heat or separation demands, it can readily expose the scenery that minimizes the high pressure steam level production. This paper seeks to show the potential of the abovementioned concept, verifying the most optimized scenery of high-pressure steam for a specific situation of loads in the referred industry. It was observed a potential of economy of 24 t/h in the generation of steam in boilers.

Keywords: Linear programming, petrochemical industry, turbine, co-generation system, steam network.

1. Introduction

The rational use of utilities (electric energy, steam, and water) represents nowadays the great challenge to assure the competitiveness and sustainability of industries.

The optimization of utility system has been explored regarding conceptual graphic tools that allows an steam network analysis and offer a better understanding of the interactions and could accelerate the application of an algorithm method (Strouvalis et al., 1998); aiding the decision of when is convenient to a factory to generate energy with an existent co-generation system or buy outer energy and heat, using MILP routine (Bojic & Stojanovic, 1998); helping the management of energy in a multi-period basis regarding a three/four level steam network; handling annual budging planning, investment decisions, electricity contract optimization, shutdown maintenance scheduling and fuel/water balance problems in a petrochemical plant with a site-model (Hirata et al., 2004); achieving benefits from an complex refinery co-generation system avoiding loss of energy in letdown valves and helping energy management problems basically using a solver tool from a common commercial spreadsheet (Milosevic & Ponhöfer, 1997).

The proposed work presents the minimization of the steam generation in a petrochemical company, which has a production of electric energy and steam by co-generation system. In the case study, the steam network is composed by four levels of pressure that supply either thermal (heat exchangers), process (strippers) or power (pumps, compressors and electric energy) demands. The steam is produced in boilers or furnaces only in the highest level of pressure and the lower levels are produced by the extraction of turbines and/or let-down valves. The application of a optimization model is proposed in a way that based on the definition of needs of electric energy generation, process loads and steam heat or separation demands, it can readily expose the scenery that minimizes the high pressure steam level production.

* To whom all correspondence should be addressed: Rod. Tabaí-Canoas, BR 386 – km 419 – Pólo Petroquímico – CEP: 95853-000 – Triunfo – RS – Brazil. Email: eduardomagalhaes@copesul.com.br

2. Motivation and Viability

A petrochemical industry and its associated second generation industries in a petrochemical site consume steam in various areas of their productive processes. These applications can be related to machine drives, stream heating, or separation processes (strippers, etc). These applications also demands different temperature and pressure conditions, needing to operate with four steam pressure levels, such as:

Super High Pressure Steam	(VS) 113 kgf/cm^{2}g and 525°C
High Pressure Steam	(VA) 42 kgf/cm^{2}g and 400°C
Medium Pressure Steam	(VM) 18 kgf/cm^{2}g and 315°C
Low Pressure Steam	(VB) 4.5 kgf/cm^{2}g and 225°C

In the case study of this work, the petrochemical industry generates VS in the Olefins Unities furnaces (70% in mass) and in the Utility Unity Boilers (30% in mass). The normal production of VS is about 1200 t/h and the other levels of steam are produced by the extraction of turbines that generate work with the feed of VS and also by pressure letdown valves with desuperheater systems to complement the needs of steam in the levels. The pressures in the VA and VM headers are controlled by acting in the relation of extracted and exhausted of the machines or by letdown valves, and this control does not necessarily generate optimized scenery, regarding the existence of seven turbines with these characteristics, in different productive units. In this case, the optimization means the minimization of the production of VS in the auxiliary boilers, obtained through the rational operation of the letdown valves and steam relief. Nevertheless, the optimization of a steam system in Rankine cycle with such dimension and complexity is not an easy problem, because of the several and different applications involved and the connections of the pressure levels (Milosevic & Ponhöfer, 1997; Eastwood & Bealing, 2003).

The potentiality in optimization (reduction of the production of VS) of the steam system is apparently huge, due to dimension of the scale of production in a petrochemical company (industry of intensive capital) and due to the continuous regime of production. Depending on the model, an annual economy of 2 to 5% of the energy bill could be achieved, besides the environmental advantages of reduction of emissions and withdrawn of superficial water (river). The most basic procedure used to administer the commitment between the demands of several steam levels and the generation of VS is the relationship of extraction and condensation in the turbo-machines (huge process compressors and turbo-generators). This is done to increase the readiness of VA or VM (in agreement with each machine) by extraction or to use all the useful energy accomplishing work (by expanding VS to exhaust steam), without extracting smaller pressure steam whose low demand would cause need of steam relief. This extraction and condensation relationship is not free – there is a balance among this both steam rates for a given load (electrical or mechanical) demanded by each machine. Within this relationship and regarding the operational and mechanical limits of the system and their equipments, however, it could be achieved an optimized distribution for each scenery of steam demands for production of energy (electric, thermal or work). Other optimization form is to alternate the operation among different drives from same equipments (example, pumps with electric motor and steam turbines drives). The total optimization of the system, however, is not the target of the current control loop of the steam system and neither is possible of being achieved by the operation people in a practical and fast way. However, the application of a computational tool that can show the best scenery (smaller generation of VS, avoiding use of pressure letdown valves and the use of relief) is very useful and can be implemented from definitions of each scenery inputs. The implementation of this tool must be evaluated by potential earnings. So, before creating a more robust and complete method, that takes into account all of the flexibilities and existent restrictions in the steam system, it is interesting to compare the operating condition of a real scenery with the optimized condition. This is proposed in this paper.

3. Scenery

The "real scenery" refers to a specific state of the steam network of the petrochemical industry, selected in a random way. In the case study, it refers to the situation of August 5 (2003), 10:30 AM, when it was being generated 1122 t/h of VS and it was observed openings in VA/VM pressure letdown valves (18 t/h), VM/VB (97.5 t/h) and the opening of VB relief valve (32.5 t/h). Some steam consumers do not possess flow measurement, and this is the case of most of the steam flows of VB level; nevertheless, there are in the company evaluations of these normal daily demands, and the application of these values leads to a balance that reflects reasonably the situation. So, using the available data, the steam material balance was defined (see Figure 1). So, the modeling of the steam network is made respecting the thermal demands and the requested power of the machines in this day and time. The model then will be submitted to an appropriate optimization routine and the result will be compared with the steam balance observed in real conditions, as a way of verifying the potential earnings.

Generating equipments: these are the steam sources of the several existent steam levels and they can be variable or fixed. Some of these sources are also consumers of steam of higher level, generating by extraction a lower class steam. Fixed steam sources are related to equipment, in which the steam consumption is fixed and dependent on the process loads, but also produce steam of smaller pressure in the outlet. Then , according to Figure 1:

- VS is generated by the furnaces (fixed generation) and auxiliary boilers (variable generation);
- VA can be generated by the turbines 12-TBC-01/21, 47-TG-01/02, 112-TBC-01 and by the letdown valves 10-PV-51 and 46-PV-12 - variable generation;
- VM can be generated by the turbines 14-TBC-01/21, 112-TBC-01 and for the letdown valves 10-PV-52 and 46-PV-13 (variable generation), as well as by other fixed generations (in example: 14-TBC-02/22, 48-B-01 B/C/D);
- VB can be generated by the letdown valves 10-PV-13, 110-PV-04 and 46-PV-14 (variable generation), as well as by other fixed generations (in example: 12-TBB-11, 114-TBC-01);

Consumers: these represent the several steam levels demands. These demands can be:

- Thermal: Heating of another fluid with steam. As the steam leaves the system definitively (as condensate or exhaust steam), these are not considered steam generator equipments;
- Process: Steam injection directly in other equipments (as strippers, ejectors). As the steam leaves the system definitively, these consumers are not steam generators equipments;
- Power: the power consumers can also be steam generator equipments, when extracted steam is produced.

Letdown Pressure Valves: these are control valves that, allied with desuperheater systems, have the function of adjust the pressure and temperature of some steam level, sending excesses to the lower level or supplying the next lower level in order to increase its pressure. The use of letdowns reduces the efficiency of the system and should be avoided.

Relief Valves: these are existent control valves in the levels of VS and VB that are used to limit the maximum pressure of these headers, discharging steam to atmosphere.

External Clients: these are all the others industries that surround the petrochemical company and consume utilities (in this case, steam) produced in the company. External clients are considered fixed consumers – the steam is process dependant and the steam leaves the company system definitively.

4. Description of the Modeling

The modeling begins with the global material balance (control volume is the Steam system), material balance of the steam headers and of the material balance in the steam generators and consumers. So, it is necessary to define:

4.1) Indexes - The indexes are used to represent the variables and they indicate the several equipments involved in the steam system. So follows:

h - VS generating Equipments

i - VA generating Equipments

j - VM generating Equipments

k - VB generating Equipments

l - CV generating Equipments

o - VS consuming Equipments

p - VA consuming Equipments or internal areas

q - VM consuming Equipments or internal areas

r - VB consuming Equipments or areas (internal or external clients)

t - VS Relief

u - VB Relief

oc - VS consuming Processes (internal only)

pc - VA consuming processes (internal or external clients)

qc - VM consuming processes (internal or external clients)

It is observed that the indexes r, t, u, oc, pc and qc refer to consumptions where the steam is eliminated definitively of the system, and so there is need to generate more steam to keep the pressure of the headers.

4.2) Variables - The variables involved in the formulation can be classified by the following way:

VS - Flow rate of super high pressure steam (t/h)

VA - Flow rate of high pressure steam (t/h)

VM - Flow rate of medium pressure steam (t/h)

VB - Flow rate of low pressure steam (t/h)

CV - Exhaust condensate flow rate, generated in surface condensers (t/h)

CM - medium pressure condensate flow rate (t/h)

CB - low pressure condensate flow rate (t/h)

The central problem, as it was mentioned above, refers to the minimization of the production of steam of super high pressure in specific scenery of load demands, detailed in the previous item. So:

I) Objective Function:

$$\text{Min} \sum_{h=1}^{Nger} VS_h$$

The material balance equations are the restrictions of equality and they define the existent dependency among the several variables:

II) Equality Restrictions:

1) material balance around the Steam system (balance between the fundamental generations in furnaces and boilers and definitive losses - condensate, steams external clients and relieves. Therefore:

$$\sum_{h=1}^{Nger} VS_h = \sum_{l=1}^{Nger} CV_e + \sum_{pc=1}^{Ncons} VA_{pc} + \sum_{qc=1}^{Ncons} VM_{qc} + + \sum_{rc=1}^{Ncons} VB_r + \sum_{t=1}^{Naliv} VS_t + \sum_{u=1}^{Naliv} VB_u + \sum_{oc=1}^{Ncons} VS_{oc}$$

2) material balance around each steam header:

2.1) Material balance in the VS header

$$\sum_{h=1}^{Nger} VS_h = \sum_{o=1}^{Ncons} VS_o + \sum_{t=1}^{Naliv} VS_t + \sum_{oc=1}^{Ncons} VS_{oc}$$

2.2) Material balance in the VA header:

$$\sum_{i=1}^{Nger} VA_i = \sum_{p=1}^{Ncons} VA_p + \sum_{pc=1}^{Ncons} VA_{pc}$$

2.3) Material balance in the VM header:

$$\sum_{j=1}^{Nger} VM_j = \sum_{q=1}^{Ncons} VM_q + \sum_{qc=1}^{Ncons} VM_{qc}$$

2.4) Material balance in the VB header

$$\sum_{k=1}^{Nger} VB_k = \sum_{r=1}^{Ncons} VB_r + \sum_{u=1}^{Naliv} VB_u$$

3) Material balance around the turbines and valves (letdown and relief valves). The turbines that have some degree of freedom were modeled to assist the load demand in the studied scenery:

3.1) **12 – C – 01**:
Material balance:

$$VS_{12C01} = VA_{12C01} + CV_{12C01}$$

Extraction relationship in the potency of the studied scenery (18 MW):

$$VA_{12C01} = 1.36\ VS_{12C01} - 104.46$$

3.2) **12 – C – 21**:
Material balance:

$$VS_{12C21} = VA_{12C21} + CV_{12C21}$$

Extraction relationship in the potency of the studied scenery (26.8 MW):

$$VA_{12C21} = 1.42\ VS_{12C21} - 163.74$$

3.3) **14 – C – 01**:
Material balance:

$$VS_{14C01} = VM_{14C01} + CV_{14C01}$$

Extraction relationship in the potency of the studied scenery (21 MW):

$$VA_{14C01} = 1.43\ VS_{14C01} - 103.81$$

3.4) **14 – C – 21**:
Material balance:

$$VS_{14C21} = VM_{14C21} + CV_{14C21}$$

Extraction relationship in the potency of the studied scenery (18.1 MW):

$$VA_{14C21} = 1.68\ VS_{14C21} - 116.61$$

3.5) **10 – PV – 51**:

$$VS_{10PV51} = VA_{10PV51}$$

3.6) **47 – TG – 01**:

Material balance:

$$VS_{47TG01} = VA_{47TG01} + CV_{47TG01}$$

Extraction relationship in the potency of the studied scenery (13.25 MW):

$$VA_{47TG01} = 1.30\ VS_{47TG01} - 74.86$$

3.7) **47 – TG – 02**:

Material balance:

$$VS_{47TG02} = VA_{47TG02} + CV_{47TG02}$$

Extraction relationship in the potency of the studied scenery (12.5 MW):

$$VA_{47TG02} = 1.21\ VS_{47TG02} - 70.00$$

3.8) **46 – PV – 12**: $VS_{46PV12} = VA_{46P12}$

3.9) **112 – C – 01**:

Material balance:

$$VS_{112C01} = VA_{112C01} + VM_{112C01}$$

Extraction relationship in the potency of the studied scenery (21 MW):

$$VA_{112C01} = 1.76\ VS_{112C01} - 360.10$$

3.10) **11 – PV – 24**: $VS_{11PV24} = VM_{11PV24}$

3.11) **10 – PV – 52**: $VA_{10PV52} = VM_{10PV52}$

3.12) **46 – PV – 13**: $VA_{46PV13} = VM_{46PV13}$

3.13) **10 – PV – 13**: $VM_{10PV13} = VB_{10PV13}$

3.14) **46 – PV – 14**: $VM_{46PV14} = VB_{46PV14}$

3.15) **110-PV-04**: $VM_{110PV04} = VB_{110PV04}$

4) **Inequalities restrictions**: these refers to the characterization of the variables as physical properties and capacities of equipments and instruments:

4.1) Physical variables:

$VA_i > 0$ $VB_u > 0$
$VM_j > 0$ $VS_t > 0$
$VB_k > 0$ $CV_l > 0$
$VS_o > 0$

4.2) Capacities of equipments and instruments (t/h):

$0<VS_{46PV24}<170$; $0<VS_{46PV25}<170$;

$0<VS_{46PV12}<310$; $0<VA_{46PV13}<220$; $0<VM_{46PV14}<60$;

$0<VB_{46PV26}<170$

$0<VS_{11PV24}<165$

$0<VS_{10PV51}<310$; $0<VA_{10PV52}<220$; $0<VM_{10PV13}<110$;

$0<VB_{10PV14}<110$;

$0<VM_{110PV04}<110$; $0<VB_{110PV01}<110$;

$143.30<VS_{12C01}<220$; $203.33<VS_{12C21}<226$;

$117<VS_{14C01}<134$; $70<VS_{14C21}<134$;

$70<VS_{47TG01}<176$; $60<VS_{47TG02}<176$;

$266<VS_{112C01}<284$;

$$0< \sum_{h=1}^{Nger} VS_h < 1600;$$

$CV_{14C01}<53$; $CV_{14C21}<53$; $CV_{12C01}<54.2$; $CV_{12C21}<69$

$CV_{47TG01}< 54$; $CV_{47TG02}< 54$;

5. Solution

Analyzing the objective function and to the restrictions above, the following form is observed:

$$f(x) = \sum_{i=1}^{r} c_i x_i$$

with $\chi_i \geq 0$ i = 1,2,....,r

and,

$$\sum_{i=1}^{r} a_{ji} x_i = b_j \qquad j = 1,2,...,m$$

and,

$$\sum_{i=1}^{r} a_{ji} x_i \geq b_j \qquad j = m + 1,...,p$$

This is a problem of multivariable linear programming (LP) - the objective function is convex and the linear restrictions form a convex region. Today there are available commercially a large amount of solvers with LP methods. In this work, the software GAMS was applied. It is an optimization platform that allows, through specific language, to formulate the problem and to solve it through the application of an optimization routine. In this problem, the algorithm OSL was used, being applied three optimization methods: simplex primal, simplex dual and interior point.

The solution can be found summarized in Figure 2. The three methods lead to the same solution. As can be observed, savings of 24 t/h of VS can be achieved if the extraction / condensation ratio of the turbines were better explored. It must be underlined that the optimized scenery lead to a condition where there was no opened relief valve and the use of letdowns was reduced – the VA/VM letdown was closed and there was a reduction of 25.4 t/h in the VM/VB letdown.

6. Conclusions

With the approach used in this work for solving the steam production optimization problem of a specific scenery, although modeled in a simplified way (turbines modeled by translating manufacturer's curve and for an specific load; steam balance using some project steam rates because of the lack of measurement; the constrains lacks some operational and mechanical limits; there was no exploration of switching electric and steam drives), the steam network balance was consistently achieved by the available data and the linear equation-based model for the equipments leads to a simple but reliable form of optimization – a linear programming. The objective to evaluate the potential earnings was successful: the magnitude of the benefit is considerable and justifies further improvements in the model and optimization method. Next steps will regard an on-line and more rigorous steam balance, which will input the steam fixed demands for any period to an optimization platform that will have a more complete turbine modeling and will include switching of motor and turbine drives. Other items in study are an evolution of the objective function to cost of steam and electric energy, both to be minimized, and the evaluation of the exergy efficiency of a scenario, before and after an optimization procedure.

References

Milosevic, Z., Ponhöfer. Refiner improves steam system with custom simulation / optimization package, Oil & Gas J., Aug. 25, 1997

Eastwood, A., Bealing, C. Optimizing the day to day operation of utility systems, Linhnhoff March, Northwich, UK, 2003.

Strouvalis, A.M., Mavromatis, S.P., Kokossis, A.C. Conceptual Optimization of Utility Networks using Hardware and Comprehensive Hardware Composites , Comput. Chem. Eng. 22 (1998) 175-182

Bojic, M., Stojanovic, B., MILP Optimization of a CHP energy System , Energy Convers. Mgmt Vol. 39 No. 7 (1998) 637-642

Hirata, K., Sakamoto, H., O´Young, L., Cheung, K.Y., Multi-site utility Integration – an industrial case study , Computers and Chemical Engineering 28 (2004) 139-148

Fig. 1: Steam Network in 08/05/2003 - 10:30 am

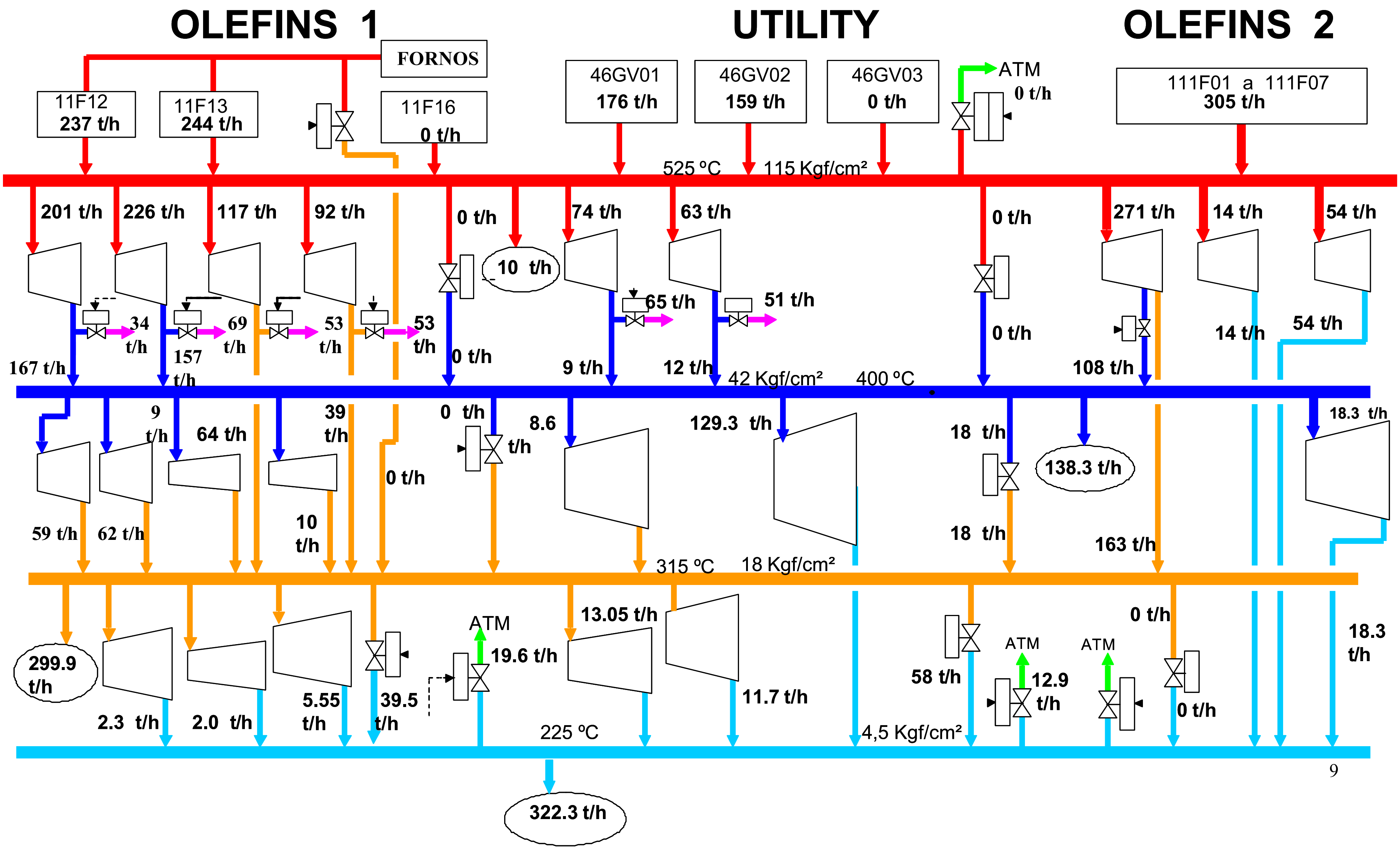

Fig. 2: Optimized scenery considering the loads of 08/05/2003 – 10:30 am