AN MILP APPROACH TO OPTIMUM LOAD ALLOCATION IN A MULTIPLE BOILERS SYSTEM

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ABSTRACT

This paper presents an approach based on mixed-integer linear programming (MILP) for the fuel consumption optimization problem in a multiple steam generation boiler system. The addressed optimization problem is typically nonlinear, however, a piecewise linearization is applied in order to solve the problem with a MILP model. Presented results indicate that it is possible to operate the system with optimum fuel consumption, only by knowing the efficiency versus load curve of each boiler composing the entire system. This paper presents the optimization problem, the MILP modeling, and the numerical resolution for a scenario based on real-world data from three water tube boilers.

KEYWORDS. Multiple boilers system, mixed-integer linear programming (MILP), energetic efficiency.

Main area. EN (OR in the Energy), IND (OR in Industry), P&G (OR in Oil and Gas).

1. Introduction

Boiler is equipment commonly found in industries and even in large buildings. Its primary function is convert fuel energy into thermal energy by generating steam to its consumers.

Thermal systems of large heat industrial consumers are usually composed of more than one boiler. These large power plants are characterized by continuous search for energy efficiency improvement, given the amount of energy involved in such equipment.

Boilers optimization is an old research topic, with first published studies dating back 20 years or more, such as the paper presented by Fogarty (1988). However, the topic still remains an active research topic due to a growing demand for energy efficiency, which is now benchmark for many industries. In this context, Liao and Dexter (2004) investigated the potential for energy savings in heating systems through improvements in the boilers control.

Mathematical modeling using linear and nonlinear programming tools is a current approach to optimize industrial boilers and power generation systems. Among the references surveyed, it can be cited Bujak (2009). The author presents a mathematical model to optimize energy of a steam generation boilers system supplied by multiple identical fired tube boilers. The author used a linear programming approach in order to minimize energy losses. Moreover, Dunn and Du (2009) presented an approach to optimize the fuel costs of a multiple boilers steam generation system. The authors used a non-linear approach to solving the problem. Rocco and Morabito (2010) presented a MILP model that aims to support the management decisions about multiple industrial boilers. The proposed model determines which boilers should be triggered to produce steam, according to some characteristics of the problem, such as, start-up costs, heating fuel, among others. It can be also cited Borghetti et al. (2008), which presented an MILP approach to the problem of production energy scheduling in a hydroelectric plant. The authors successfully used a piecewise linearization technique to handle non-linear constraints.

This paper aims to study the optimal fuel consumption problem in a multiple boilers steam generation system. It presents a mixed-integer linear programming approach in which the curve of fuel consumption versus mass flow rate of steam produced by each boiler will be approximated by piecewise linearization. To achieve balance in a steam generation system, the consumption steam flow required by consumers must be equal to the sum of the boilers generated steam flow. Therefore, there are countless possibilities to combine steam supply from boilers in order to attain this requirement. The proposed model goal is to point the ideal steam flow supplied by each boiler to compose the total demand required by consumers. So that, the whole system can operate in the optimum fuel consumption point. These ideal steam flow values to be supplied by each boiler can then be used in an expert system to support operational decisions, or even as set-points to steam flow controllers of boilers.

2. The optimization problem

In multiple boilers systems, the dynamic behavior of steam generation system is result of the interaction between each boiler and steam consumer units. Figure 1 shows a simplified system (just fuel and steam connections) with three boilers, highlighting its hydraulic links. This main system concern is to keep the steam header at a specified pressure. To achieve that, the mass balance between the sum of steam provided by each boiler (in Figure 1, q_{s1}, q_{s2}, and q_{s3}) should be equal to the total consumption of steam consumers (q_{sdem}). If steam generation is greater than demand, the system pressure will increase. In the other hand, if steam generation is smaller than demand of consumers, the system pressure will drop.

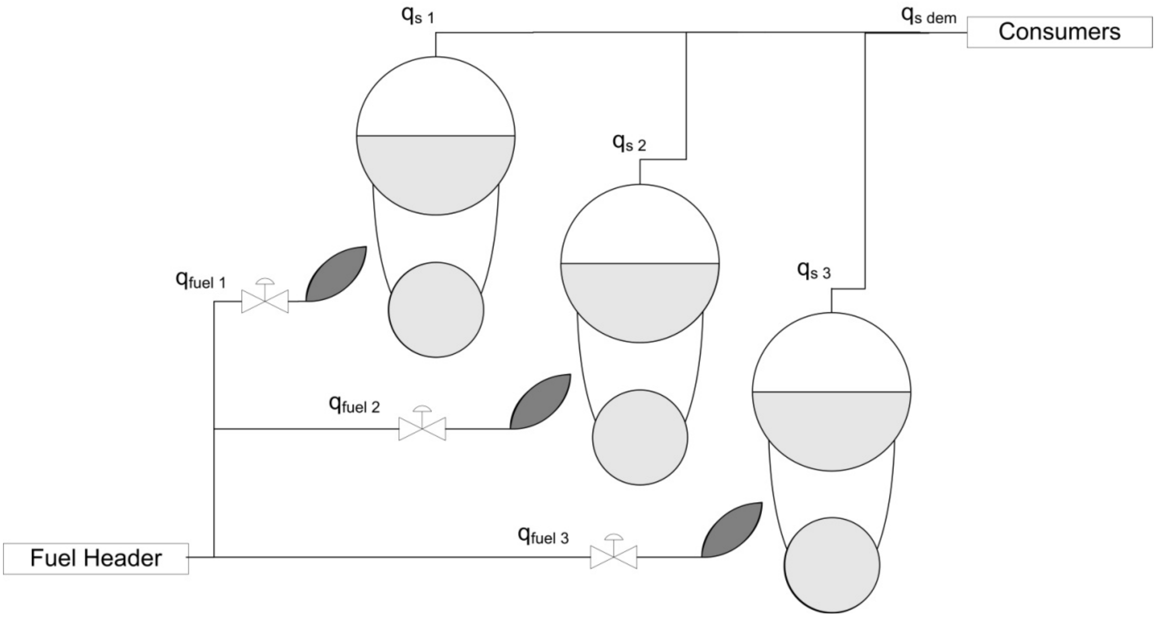

Figure 1. Main hydraulic connections of a three boiler steam generation system.

The nomenclature used for the mathematical model is herein presented:

Indexes:

- g: represents each boiler;
- s: represents each linearised segment.

Parameters:

- $A_{g\,s}$: slope of each line segment s of a boiler g;
- $B_{g\,s}$: linear coefficient of each line segment s of a boiler g;
- G: total number of boilers in the system;
- h_s: enthalpy of saturated steam produced by any boiler [kcal/kg];
- h_f: enthalpy of feedwater supplied to any boiler [kcal/kg];
- $Lim_{\,g\,s}$: limits to produced steam flow rate of each line segment s of a boiler g [kg/s];
- LCV: fuel lower calorific value [kcal/kg];
- q_{sdem}: total steam flow demanded by the system [kg/s];
- S: number of line segments, where $q_{fuel\,g}$ is piecewise linearised.

Variables:

- $\eta_{ef\,g}$: dimensionless efficiency of a boiler g;
- $Op_{\,g\,s}$: binary variable defining, when in logic level 1, which boiler g is exactly operating within line segment s limits;
- $q_{fuel\,g}$: fuel flow rate of a boiler g [kg/s];
- $q_{fuel\,g\,s}$: fuel flow rate of a line segment s of a boiler g [kg/s];
- $q_{s\,g}$: steam mass flow generated (also known as load) by a boiler g [kg/s];
- $q_{s\,g\,s}$: steam mass flow generated of a line segment s of a boiler g [kg/s].

The system economic objective is to meet steam demand of consumer units, with a minimum expense of fuel. Thus, the objective function is defined according to equation (1).

$$\min z = \sum_{g=1}^{G} q_{fuel\ g} \tag{1}$$

The boiler efficiency is defined as the ratio of energy transferred to water (steam production) and energy provided by fuel. Thus, it is possible to write fuel consumption of each boiler as given by equation (2).

$$q_{fuel\ g} = \frac{(h_s - h_f) q_{s\ g}}{\eta_{ef\ g} LCV} \quad \forall g \in G \tag{2}$$

Finally, the system mass balance must be kept in steady state. So that, equation (3) must hold.

$$q_{sdem} = \sum_{g=1}^{G} q_{s\ g} \tag{3}$$

3. The MILP modeling

Boilers have typical efficiency curves that depend on several parameters, such as, mechanical design and operating conditions related to excess air, flue gas temperature, local temperature, tuning points of boiler control loops, and combustion load (LIPTAK, 2006). Typically, boilers have a point of maximum efficiency in their efficiency versus produced steam flow curve, as illustrated in Figure 2.

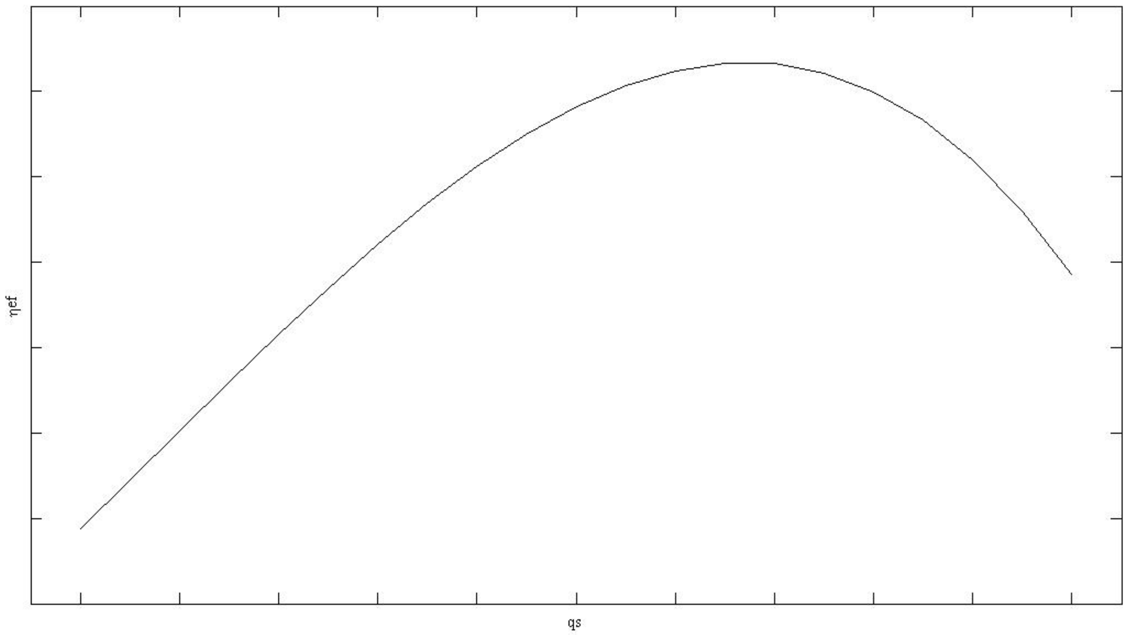

Figure 2. Boiler efficiency curve (η_{ef}) as function of the produced steam flow (q_s).

Figure 2 shows that the efficiency behavior is a nonlinear function ($\eta_{ef} = \varphi(q_s)$) of boiler load. Based on equations (1) and (2) and also on function $\eta_{ef} = \varphi(q_s)$, the resulting optimization problem has nonlinear features. For instance, the numerator of equation (2) is a term involving the variable q_s and the denominator is a term including η_{ef}. However, through a model including binary decision variables, it is possible to transform this nonlinear problem into a mixed-integer linear programming (MILP) problem by piecewise linearization, such as the work presented by Borghetti et al. (2008).

To perform a piecewise linearization, initially, the function $\eta_{ef} = \varphi(q_s)$ is applied in equation (2). Then, different q_s values are tested in order to obtain the behavior of the produced steam flow versus fuel consumption, as shown in Figure 3.

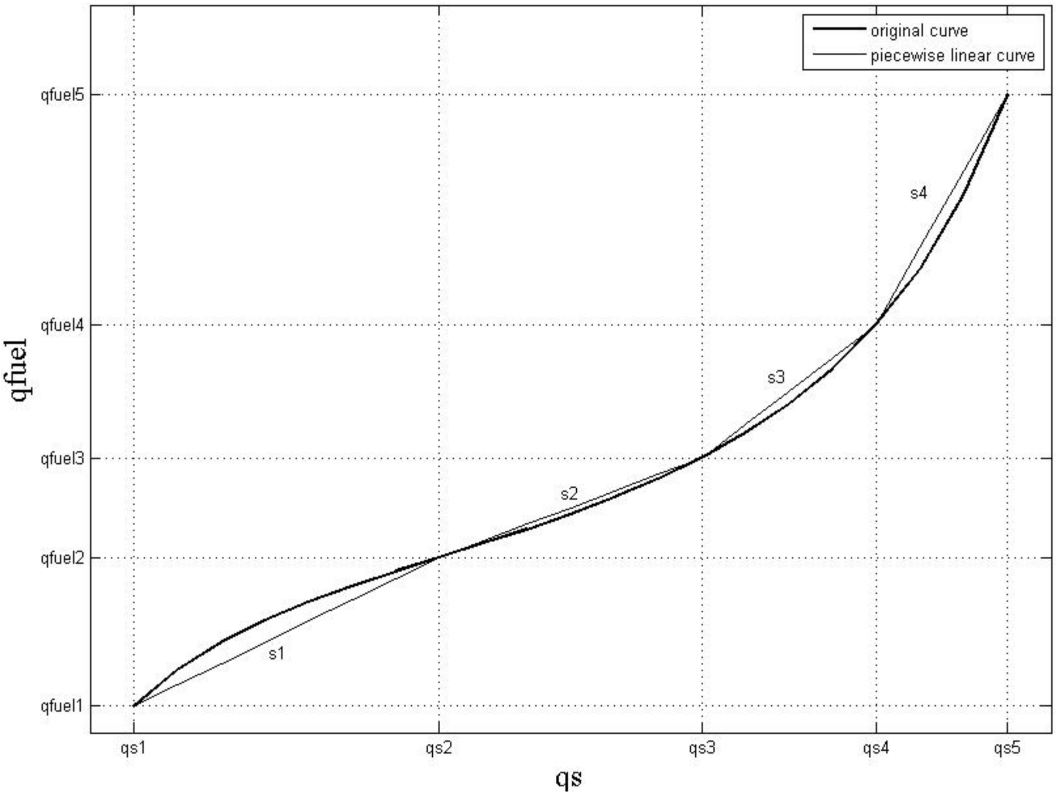

Figure 3. Boiler fuel consumption as function of load.

Figure 3 shows the boiler fuel consumption plot as function of boiler load. This figure also indicates an example of the piecewise linearized plot function desired to this curve. In this example, the original plot is decomposed into four linear sections (indicated by s1 to s4). At this point, it is important to note that each linear segment is defined by its linear coefficients and by lower and upper boundaries of fuel flow. These parameters will be used in the model for the piecewise linearization.

Thus, with the objective function given in equation (1) and constraints given in equations (2) and (3), additional constraints to generate the piecewise linearization required were built.

Equation (4) defines that the produced steam flow by each boiler is the sum of the steam flow of each linearized segment.

$$q_{s\,g} = \sum_{s=1}^{S} q_{s\,gs} \qquad \forall g \in G \qquad (4)$$

Equation (5) models the constraint defining that the consumed fuel flow by each boiler is the sum of the fuel flow of each linearized segment.

$$q_{fuel\,g} = \sum_{s=1}^{S} q_{fuel\,gs} \qquad \forall g \in G \qquad (5)$$

Equation (6) presents the consumed fuel flow by each boiler as a function of the produced steam flow (straight line equation).

$$q_{fuel\,gs} = A_{gs} q_{s\,gs} + B_{gs} Op_{gs} \qquad \forall g \in G, s \in S \qquad (6)$$

Inequalities (7) and (8) present a Big-M formulation (WILLIANS, 1999), allowing the produced steam flow to be non-null only at an active boiler segment.

$$q_{s\,gs} \leq Lim_{g\,(s+1)} Op_{gs} \qquad \forall g \in G, s \in S \qquad (7)$$

$$q_{s\,gs} \geq Lim_{g\,s} Op_{gs} \qquad \forall g \in G, s \in S \qquad (8)$$

Finally, equation (9) shows the constraint defining that each boiler has one, and only one, active linearized segment. Thus, as long as the results are aimed to be used in automatic control and usually start up is a manual operation, in this case study any boiler will always be considered operating at one of the linearized levels in this model.

$$\sum_{s=1}^{S} Op_{gs} = 1 \qquad \forall g \in G \qquad (9)$$

Equation (9) must be rewritten if a wider scenario, including boiler shutdown or start-up conditions, were considered. In this case, equation (9) has to be replaced by an inequality where the sum of the binary variables must be less than or equal to 1.

4. Results and discussions

It was considered in this section a steam generation system with three watertube boilers. This system is similar to one found at a Brazilian oil refinery. The boilers performance curves (efficiency versus load) are presented in Figure 4. As long as the boiler is operating, it must provide a minimum load, so it can be shown in Figure 4 that the boilers are not allowed to provide zero load in this case study.

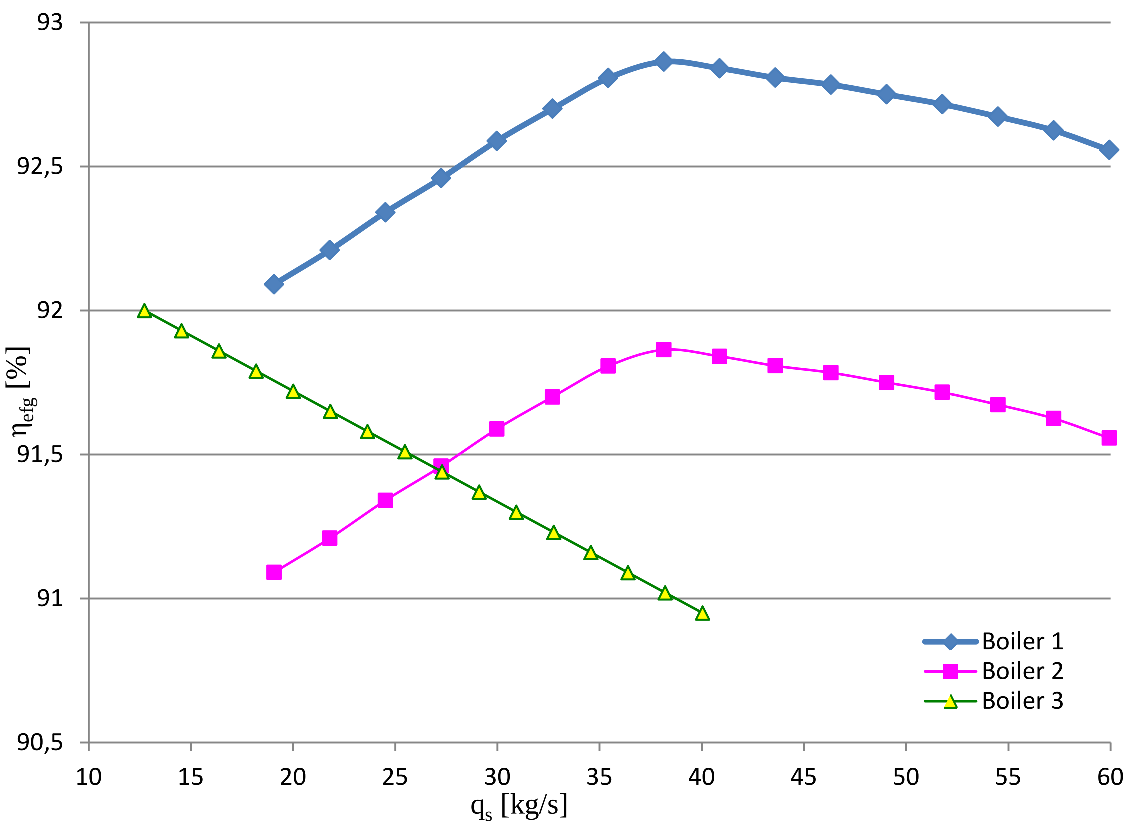

Figure 4. Boilers performance curves (efficiency versus load).

The MILP model was built using GUSEK – GLPK *Under SciTE Extended Kit* –

(GUSEK, 2013), a freeware software that allows the development of MILP models in an IDE (Integrated Development Environment) for Windows. GUSEK packs a custom version of the *SciTE* editor linked to the GLPK standalone solver (GLPK, 2013). Thus, generated models are solved by the GLPK solver.

For scenario numerical resolution, some operational conditions are assumed: fuel has *LCV 11300 kcal/kg*, generated steam has h_s *800 kcal/kg*, and feedwater has h_f *148 kcal/kg*. Also, the boiler fuel consumption as a function of the boiler load is piecewise linearized into 15 linear sections.

By changing system demanded steam flow (q_{sdem}), it is possible to obtain several system operational points (which are characterized by the total steam flow consumption), corresponding to the contribution of each boiler in order to obtain the optimum fuel consumption.

Figure 5 presents in a graphical way some model results obtained with GUSEK IDE and GLPK solver.

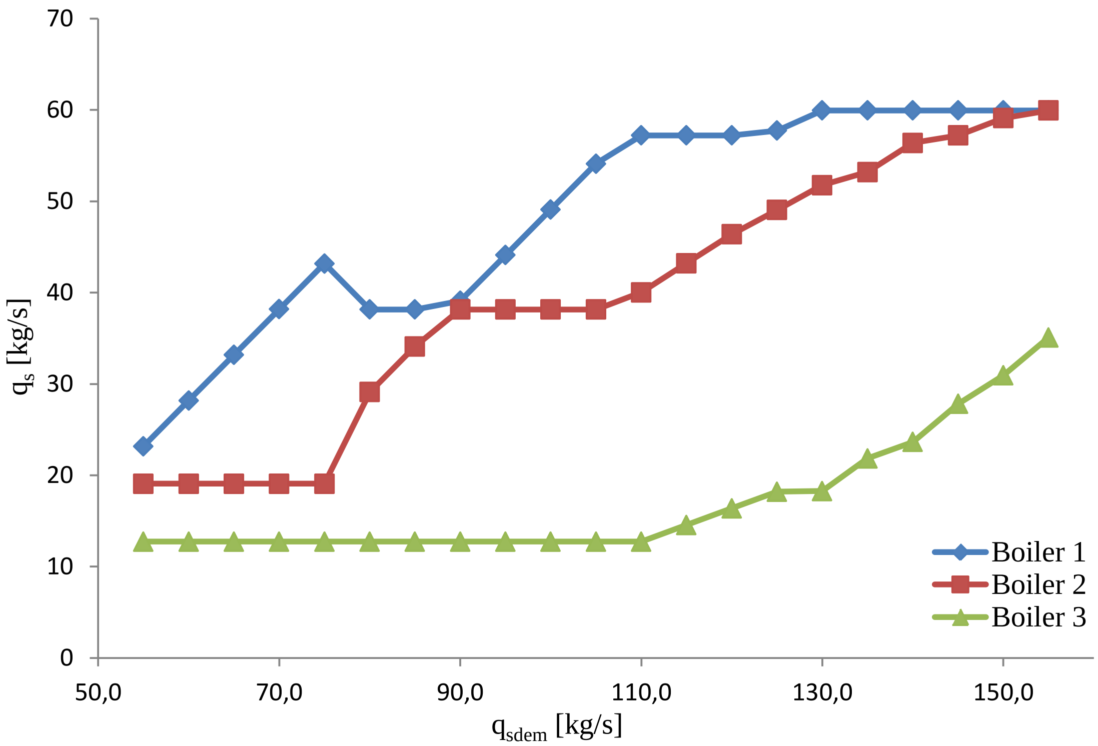

Figure 5. Load of each boiler as function of the total steam flow required by consumers.

It can be noted from figure 5 that the higher steam flow is delivered to system by Boiler 1. This behavior is expected, since this boiler has higher efficiency values when compared to other boilers, as shown in figure 4.

Table 1 illustrates the fuel economy (column Economy [%]) that can be obtained by the proposed model in relation to the worst case system operation. Initially the solutions for the proposed MILP model (column Minimum total fuel) were computed for different total demands of consumers (column q_{sdem}). Afterwards, the objective function (equation (1)) is modified to maximization. In this case, the solution for the modified MILP model returns the worst case operation condition, that is, the case where the fuel consumption is maximized. Solutions for different levels of total demands of consumers (column q_{sdem}) are also given in table 1 (column Maximum total fuel) for the modified MILP model. The possible fuel economy is obtained by comparing the columns Minimum total fuel with Maximum total fuel.

q_{sdem} [kg/s]	Minimum total fuel [kg/s]	Maximum total fuel [kg/s]	Economy [%]
55.00	3.4569	3.4620	0.15
60.00	3.7653	3.7790	0.36
65.00	4.0723	4.0973	0.61
70.00	4.3798	4.4170	0.84
75.00	4.6920	4.7380	0.97
80.00	5.0040	5.0570	1.05
85.00	5.3143	5.3693	1.02
90.00	5.6254	5.6802	0.96
95.00	5.9377	5.9904	0.88
100.00	6.2503	6.3039	0.85
105.00	6.5639	6.6197	0.84
110.00	6.8788	6.9361	0.83
115.00	7.1944	7.2537	0.82
120.00	7.5102	7.5713	0.81
125.00	7.8266	7.8806	0.68
130.00	8.1432	8.1883	0.55
135.00	8.4605	8.4952	0.41
140.00	8.7784	8.8046	0.30
145.00	9.0970	9.1169	0.22
150.00	9.4168	9.4297	0.14
155.00	9.7374	9.7435	0.06

Table 1: Comparison between solutions of maximum versus minimum total fuel consumption

Table 1 shows that fuel consumption values can be up to 1.05% smaller than an operating condition in which consumption is maximum. Remember that the curves of boilers efficiency are distance themselves from each other at around 1%, as shown in figure 4.

Although the model presented in this paper minimizes the fuel consumption, it can be easily modified to minimize fuel costs. Thus, different fuel scenarios can be evaluated to reduce the system operation costs.

5. Conclusions

This paper proposed an MILP approach for fuel consumption optimization in a multiple boilers steam generation system. In this approach, it is necessary to know only the total efficiency versus boiler load plot. This curve can be obtained from practical experiments and boiler thermal models. However, the proposed approach is only valid to system steady state conditions, since boiler load dynamic transitions are not modeled.

The presented results indicate that it is possible to operate multiple boilers steam generation system at the optimum fuel consumption point. The computed optimal parameters to each boiler can be used in an expert system to support system operational management, or even to compose set-points to load controllers of each boiler.

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