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Energy savings and heat efficiency in the paper industry: A case study of a corrugated board machine

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ABSTRACT

The paper presents the improvement of energy management in a steam system used for corrugated board production. The system consists of a steam boiler (fired with natural gas), steam and condensate pipelines and a corrugated board production installation (steam consumer). In the existing system, the boiler works in unison with an open condensate tank. This tank is responsible for energy losses due to secondary steaming. Therefore, a system of a closed tank has been proposed to eliminate these energy losses. The coefficients of thermal performance and the energy losses in both cases (open and closed tank) are compared. The study shows that the losses of the closed steam system are always lower than those of the open system. The coefficient of performance could be increased by about 8% by the proposed modernization. The recovery of expenses for modernization should be very quick, taking place within a year.

1. Introduction

Condensate and steam systems are mainly used in industrial plants where saturated steam is supplied to various technological processes. Such systems consist of three basic elements: output, transfer and receiving elements. Each component loses energy and, as a consequence, the thermal performance of the overall system is lowered.

A number of papers have been written recently about the energy and heat performance of steam systems as well as their individual components. One of the most important processes influencing the performance of a steam and condensate system is heat exchange efficiency in the steam boiler furnaces. Steam boilers belong to the output element. To start with, Huang et al. [1] presented a fire-tube boiler model to examine its thermal performance. The modelling considers the heat exchange between the flue gases and the boiling water, and the heat exchange between the external surface of the boiler and the environment. Applying this kind of model, we can simulate boiler performance at different heat loads. Next, Gürüz [2] described a mathematical model of heat exchange in the furnace taking into account its soot deposit. Subsequently, Niu and Wong [3] presented a mathematical model of a combustion chamber and boiler heaters with an example of a boiler unit with a capacity of 2614091 kg/h generating superheated steam. Bueters et al. [4] and Richter and Payne [5] also presented similar models and studied their thermal performance. Next, Bujak and Bałdyga [6], using a mathematical model, examined the influence of the steam boiler blow-off on its thermal performance in the function of heat load, and at different feed water salinities. The analysis [6] was carried out using two methods. The first method involved fire-tube shell boilers generating saturated steam and the second method involved generating superheated steam. Rusinowski and Stanek [7] presented neural modelling of the steam boilers. Neural modelling analyses consider the influence on thermal performance of the boiler of heat lost as flue gases, unburned combustibles in slag, unburned combustibles in flue dust, or the heat lost through the external boiler surface to the environment. Bujak [8] tested the influence of energy losses on thermal performance of the shell boiler due to ventilation of the boiler combustion chamber. He presented a simple formula for determining the losses and discussed methods for their reduction. Bujak showed a relationship between the heat load of the boiler, as well as its internal operating saturated steam pressure, and energy losses. Finally, Bhatt [9] showed energy audit case studies for steam systems. He presented an analytical and diagnostic device for an energy audit of steam systems, which is then applied to a few industrial cases.

Steam systems are widespread in the paper industry. A method for identifying and characterizing technologies that can improve the energy efficiency in the long term is also described by Beer et al. [10] and has been applied to the paper and board industry. Seven relevant technologies are described in that article. Optimal energy management in pulp and paper mills is presented in [11] by Sarimveis et al. They examined the utilization of mathematical

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Nomenclature

A surface of heat exchange (m^2)
A_0 area of diaphragm (m^2)
c_{fg} specific heat of flue gas (kJ/kg K)
$\dot{E}_{l-bd}$ enthalpy flux of water from the boiler blow-down (kW)
$\dot{E}_{l-bo}$ enthalpy flux of water from the boiler blow-off (kW)
$\dot{E}_{l-chl}$ enthalpy flux of flue gases (kW)
$\dot{E}_{l-chv}$ enthalpy flux of air used for the ventilation of the boiler combustion chamber during the ventilating burner start (kW)
$\dot{E}_{l-esie}$ heat flux lost to the atmosphere through the boiler external surface (kW)
$\dot{E}_{l-es(d+f)}$ heat flux lost to the atmosphere through the external surface of the degassing heater and the feed water tank (kW)
$\dot{E}_{l-esfp}$ heat flux lost to the atmosphere through the external surface of fittings and output element pipelines (in a boiler plant and transfer element) (kW)
$\dot{E}_{l-ic}$ chemical enthalpy flux of flue gases—incomplete combustion (kW)
$\dot{E}_{l-sed}$ enthalpy flux of steam lost to the atmosphere due to saturated steam evaporation through the degassing heater (kW)
$\dot{E}_{l-sv}$ enthalpy flux of steam lost to the atmosphere due to secondary steaming in the condensate tank (kW)
$\dot{E}_{o-oe}$ enthalpy and heat flux carried away from the steam output element (primary side) (kW)
$\dot{E}_{s-a}$ enthalpy flux of air supplied to the output element for the combustion process (kW)
$\dot{E}_{s-ng}$ enthalpy flux of natural gas (fuel) supplied to the output element (kW)
$\dot{E}_{s-oe}$ enthalpy and heat flux supplied to the steam output element (primary side) (kW)
$\dot{E}_{s-sw}$ enthalpy flux of makeup water supplied to the steam system (kW)
$\dot{E}_{th}$ total flux of heat and enthalpy supplied to the optional system (kW)
$\dot{E}_{u}$ usable heat flux carried away from the optional system (kW)
$\dot{E}_{u-cbm}$ usable enthalpy flux supplied to the corrugated board machine (kW)
G_{SB} steam boiler capacity (t/h)
h_{bdw} water enthalpy carried away from the steam boiler due to its blow-down (kJ/kg)
h_{bo} water enthalpy carried away from the steam boiler due to its blow-off (kJ/kg)
$h_{ss\text{-}c}$ enthalpy of saturated steam carried away to the environment due to the steaming of the deaerating heater column (kJ/kg)
H_{co} calorific value of carbon monoxide (kJ/kg)
K_V flow ratio of a valve (m^3/h)
L length of steam and condensate pipes (m)
m_{bdw} flux of water mass carried away from the boiler due to its blow-down (kg/s)
m_{fg} flux of flue gases mass (kg/s)
m_{ss} flux of saturated steam mass produced by the steam boiler (kg/s)
$m_{ss\text{-}c}$ flux of saturated steam mass carried away to the environment due to deaerating heater column steaming (kg/s)
n number of burner blow-off cycles
p_1 operating pressure of saturated steam in a steam boiler (bar)
p_2 operating pressure of saturated steam in a pressure tank (bar)
$s_{s\text{-}fw}$ concentration of salt or silica in water feeding a steam boiler (mg/l)
$s_{s\text{-}max}$ maximum concentration of salt or silica in water feeding a steam boiler (mg/l)
Q_{sb} usable power of steam boiler (kW)
t_e temperature outside the pipeline or tank (reference level 25 °C)
t_{fg} flue gas temperature (°C)
t_i steam or condensate temperature inside the pipeline or tank (°C)
t_{ref} reference temperature (reference level 25 °C)
t_1 saturated steam temperature at the boiler output (°C)
t_2 condensate temperature after the board machine (°C)
t_{2m} mean condensate temperature after the board machine obtained during the testing period (°C)
t_{2max} maximum condensate temperature after the board machine obtained during the testing period (°C)
t_{2min} minimum condensate temperature after the board machine obtained during the testing period (°C)
t_3 condensate temperature after the condensate tank (°C)
t_{3max} maximum condensate temperature after the condensate tank (before the economizer) obtained during the testing period (°C)
t_{3min} minimum condensate temperature after the condensate tank (before the economizer) obtained during the testing period (°C)
t_4 condensate temperature after the economizer (°C)
t_{4max} maximum condensate temperature after the economizer obtained during the testing period (°C)
t_{4min} minimum condensate temperature after the economizer obtained during the testing period (°C)
t_5 natural gas temperature (°C)
t_6 temperature of air used for combustion process (°C)
U coefficient of heat transmission (W/m^2 K)
x_{co} weight in weight concentration of carbon monoxide in flue gases (kg/kg)
x_h content of humidity in air (g/kg)

Greek letters

α coefficient of discharge
$\Delta\dot{E}_{hl-oe}$ enthalpy and heat flux lost in the output element (kW)
$\Delta\dot{E}^{1}_{hl-oe}$ enthalpy and heat flux lost in the output element without considering losses due to secondary steaming in the condensate tank (kW)
$\Delta\dot{E}_{hl-te}$ heat flux lost in the transfer element (kW)
$\Delta\varepsilon_{ss\text{-}max}$ maximal measurement uncertainty of the coefficient of thermal performance (%)
$\Delta\varepsilon_{ss\text{-}p}$ probable measurement uncertainty of the coefficient of thermal performance (%)
Δp_{bdw} differential pressure before and after the blow-down valve (bar)
Δp_{sed} differential pressure before and after the diaphragm (N/m^2)
$\left|\frac{\partial\varepsilon}{\partial x_1}\right|\Delta X_1$ maximal measurement uncertainty of X_1, the measurement of heat in saturated steam—HM (%)
$\left|\frac{\partial\varepsilon}{\partial x_2}\right|\Delta X_2$ maximal measurement uncertainty of X_2, the measurement of heat in natural gas—GM (%)