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Energy, exergy and economic analysis of industrial boilers

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ABSTRACT

In this paper, the useful concept of energy and exergy utilization is analyzed, and applied to the boiler system. Energy and exergy flows in a boiler have been shown in this paper. The energy and exergy efficiencies have been determined as well. In a boiler, the energy and exergy efficiencies are found to be 72.46% and 24.89%, respectively. A boiler energy and exergy efficiencies are compared with others work as well. It has been found that the combustion chamber is the major contributor for exergy destruction followed by heat exchanger of a boiler system. Furthermore, several energy saving measures such as use of variable speed drive in boiler's fan energy savings and heat recovery from flue gas are applied in reducing a boiler energy use. It has been found that the payback period is about 1 yr for heat recovery from a boiler flue gas. The payback period for using VSD with 19 kW motor found to be economically viable for energy savings in a boiler fan.

1. Introduction

Nearly 45% of global electricity generation is derived from coal while natural gas and nuclear energy makes up about 20% and 15%, respectively of the world's electricity generation (Energy information administration, 2007). Since these energy sources generally use boiler–steam turbine system to convert its chemical potential energy to electricity generation, one can only imagine the possible way of savings derivable from improving the efficiency of a steam boiler by just a small fraction. Most of the heating systems, although not all, employ boilers to produce hot water or steam.

All of the major industrial energy users devote significant proportions of their fossil fuel consumption to steam production: food processing (57%), pulp and paper (81%), chemicals (42%), petroleum refining (23%), and primary metals (10%). Since industrial systems are very diverse, but often have major steam systems in common, it makes a useful target for energy efficiency measures (Einstein et al., 2001).

Boiler efficiency therefore has a great influence on heating-related energy savings. It is therefore important to maximize the heat transfer to the water and minimize the heat losses in the boiler. Heat can be lost from boilers by a variety of methods, including hot flue gas losses, radiation losses and, in the case of steam boilers, blow-down losses (ERC, 2004) etc. To optimize the operation of a boiler plant, it is necessary to identify where energy wastage is likely to occur. A significant amount of energy is lost through flue gases as all the heat produced by the burning fuel cannot be transferred to water or steam in the boiler. As the temperature of the flue gas leaving a boiler typically ranges from 150 to 250 °C, about 10–30% of the heat energy is lost through it. A typical heat balance in a boiler is shown in Fig. 1. Since most of the heat losses from the boiler appear as heat in the flue gas, the recovery of this heat can result in substantial energy savings (Jayamaha, 2008,Beggs, 2002).This indicates that there is huge savings potentials of a boiler energy savings by minimizing its losses. Having been around for centuries, the technology involved in a boiler can be seen as having reached a plateau, with even marginal increase in efficiency painstakingly hard to achieve (Sonia and Rubin, 2007).

The First Law of Thermodynamics is conventionally used to analyze the energy utilization, but it is unable to account the quality aspect of energy. That is where exergy analysis becomes relevant. Exergy is the consequent of Second Law of Thermodynamics. It is a property that enables us to determine the useful work potential of a given amount of energy at some specified state. Exergy analysis has been widely used in design, simulation and performance evaluation of thermal and thermo-chemical systems. The energy use of a country has been assessed using exergy analysis to gain insight of its efficiency and potential for further improvement. Exergy investigations of the energy use were first introduced in USA by Reistad (1975) and have been carried out for various countries such as Canada (Rosen, 1992) Japan, Finland and Sweden (Wall, 1990), Italy (Wall et al., 1994), Turkey (Ozdogan and Arikol, 1995; Rosen and Dincer, 1997; Utlu and Hepbasli, 2003, 2005), UK (Hammond and Stepleton, 2001), Norway (Ertasvag and Mielnik, 2000; Ertasvag, 2005), China (Xi and Chen, 2005), Malaysia (Saidur et al., 2007a, b, c, Saidur

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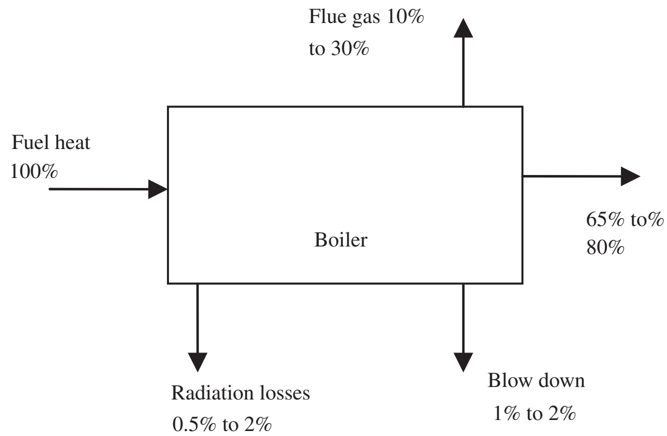

Fig. 1. Typical heat balance of a boiler (Jayamaha, 2008).

et al., 2006) and Saudi Arabia (Dincer et al., 2004a, b, c). Kanoglu et al. (2005, 2007), Som and Datta (2008), Szargut et al. (1988), Al-Ghandoor et al. (2009), Karakus et al. (2002), Kotas (1985), Rivero and Anaya (1997), and Hammond and Stepleton (2001) presented energy and exergy analysis for different industrial processes and systems for different countries.

Dincer et al. (2004a) discussed that exergy appears to be a key concept, since it is a linkage between the physical and engineering world and the surrounding environment, and expresses the true efficiency of engineering systems, which makes it a useful concept to find improvements.

As a complement to the present materials and energy balances, exergy calculations can provide increased and deeper insight into the process, as well as new unforeseen ideas for improvements. Consequently, it can be highlighted that the potential usefulness of exergy analysis in sectoral energy utilization is substantial and that the role of exergy in energy policy making activities is crucial (Dincer et al., 2004b).

An understanding of both energy and exergy efficiencies is essential for designing, analyzing, optimizing and improving energy systems through appropriate energy policies and strategies. If such policies and strategies are in place, numerous measures can be applied to improve the efficiency of industrial boilers (Kanoglu et al., 2007).

An exergy analysis is usually aimed to determine the maximum performance of the system and/or identify the sites of exergy destruction. Identifying the main sites of exergy destruction, causes of destruction, true magnitude of destructions, shows the direction for potential improvements for the system and components, (Kanoglu et al., 2005, 2007). Dincer (2002a–b) reported the relation between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making in details. So from the above discussions and literatures it is obvious that analysis of exergy is crucial for energy planning, resource optimization and global environmental, regional, and national pollution reduction.

Exergy analysis that may be regarded as accounting of the use of energy and material resources provides information as to how effective and how balanced a process is in the matter of conserving natural resources (Szargut et al., 1988). This type of information makes it possible to identify areas in which technical and other improvements could be undertaken and indicates the priorities that could be assigned to conservation procedures. Exergy conscious utilization of energy sources would help advance technological development towards resource-saving and efficient technology can be achieved by improving design of processes with high exergetic efficiency. Application of the exergy analysis in design and development of sustainable processes also provides information for long-term planning of resource management (Kotas, 1985).

Jamil (1994) studied thermodynamics performance of Ghazlan power plant in Saudi Arabia where mixture of methane, ethane and propane were used as fuels. Author found that exergy efficiency in the boiler furnace was about 18.88%. Author also found the total losses are high in the boiler especially in the heat exchanger (43.4%) compared to other devices. Author also studied Qurayyah power plant whee exergy efficiency in the furnace was about 16.88% and in the heat exchanger 25.19%.

Gonzalez (1998) studied the improvement of boiler performance by using economizer model. Author used hot gases recovery system to improve the performance of the boiler. Author reported that up to 57% of cost can be saved with the heat recovery system.

In this study energy, exergy efficiency, energy losses, and exergy detruction for a boiler is identified and ways to reduce boiler energy consumption using variable speed drive and nanofluids to enhance heat transfer applied and energy and economic benefit have been analyzed. It may be noted that a boiler energy use can be reduced by many other ways for example by controlling excess air, enhancing heat transfer rate, improving combustion efficiency, use of more environmental friendly fuel, recovering waste heat, recovering condensate, optimizing blowdown process, preventing leakage and providing proper insulation. Economic benefits associated with energy savings has been analyzed and presented as well.

It is important to note that exergy destructions are due to irreversibilities in the turbine, pump and condenser. The primary way of keeping the exergy destruction in a combustion process within a reasonable limit is to reduce the irreversibility in heat conduction through proper control of physical processes and chemical reactions resulting in a high value of flame temperature but lower values of temperature gradients within the system. The optimum operating condition in this context can be determined from the parametric studies on combustion irreversibilities with operating parameters in different types of flames. The most efficient performance is achieved when the exergy loss in the process is the minimum. These can be done by optimizing heat exchangers, fins, thermal insulation, combustion process (Som and Datta, 2008).

In this study exergy analysis on a boiler is done according to the method used by Rosen (1999) and Aljundi (2009b). As a boiler is used in many industrial applications and use significant amount of energy, its efficiency improvement and reduced losses/exergy destruction will play a significant role in energy savings and mitigation of environmental pollution. It may be stated that this study will be useful to policy makers, engineers, industrial energy users and scientist in industrial boiler energy use.

2. General mathematical tools for analysis

This section discussed several basic quantities and mathematical relations for the energy and exergy analysis.

2.1. Chemical exergy

At near ambient conditions, Dincer et al. (2004a) described that specific exergy of hydrocarbon fuels reduces to chemical exergy and can be written as

$$\varepsilon_{ff} = \gamma_{ff} H_{ff} \tag{1}$$

Where γ_{ff} denotes the fuel exergy grade function, defined as the ratio of fuel chemical exergy and heating value. Table 1 shows