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Study on The Improvement of Heat Recovery Steam Generator Efficiency – A Review

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ABSTRACT

Boilers are widely used in industries to produce steam. In some sectors, the steam generated is utilized directly in the production line for heating. Certain industries use steam to produce electricity. Fire tube boilers are limited to generating steam for processing; meanwhile, water tube boilers are widely used in electricity generation besides steam generation for processing lines. Subcritical boilers, supercritical boilers, and Heat Recovery Steam Generator (HRSG) are types of boilers commonly used to produce high capacity steam. This review article focuses on the optimization of HRSG operational efficiency. Industry players are keen on the improvement of operational efficiency since these directly influence the operating cost. Steam pressure, steam output, heat transfer efficiency and temperature distributions are key areas comprehensively reviewed in this article. Generally, improvement studies on boilers are not feasible to conduct during operation. Therefore, the scaled-down model used in the experiment or the boilers CFD models are simulated to understand the characteristics of the boilers. This review article is expected to overview HRSG boiler efficiency improvements and factors influencing boiler operational parameters.

1. Introduction

Steam generators are generally known as boilers. Boilers are the complex structure of heat exchangers which contain a bundle of tubes hold together in a shell. Boilers mainly categorize based on fuel, type of working fluid, operating pressure, number of combustion gas passes, firing arrangement and flow location [1]. Flow location is one of the well-accepted categories to identify the type of boiler. Boilers were identified based on two types of flow: a fire tube boiler and a water tube boiler.

Water-tube boiler's tubes, contain water and are surrounded by hot gas. Meanwhile, fire tube boiler's tubes have hot gas on the inside and are surrounded by water outside. Industrially common boilers are fire tube boilers where generally comes as packaged boilers. Packaged boilers are

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assembled and tested in the factory. This type of boiler is commonly used in industrial heating. Commonly used water tube boilers are circulating fluidized bed and pulverized coal fired boilers. Fluidized bed boilers are boilers containing hot bed fuel particles where the air is blown to create combustion. The heat generated is then used to convert water to steam.

Meanwhile, pulverized fuel boilers use fine powder sprayed into the furnace [2, 3]. The main difference between the fluidized bed boiler and the pulverized boiler is that the fluidized bed boiler has a refectory in the furnace to avoid erosion. Waste heat recovery boilers use exhaust heat from the gas turbine and recover the energy from the hot exhaust gas. This type of heat recovery boiler is commonly used in cogeneration plants and combined cycle power plants. Hike in fuel price and diminishing fossil fuel resources were an important factor to ensure the HRSG operations are efficient [4]. Therefore, the objective of this review is to insight studies covered various aspect of improvement in HRSG efficiency. Gas turbine exhaust gas mass flow rate and temperature been an important criterion in designing and arrangement of HRSG where, the inlet parameters are mainly studied [5-7]. Besides, HRSG designs and arrangements, operational efficiency focus by researchers since the operation efficiency able to reduce the operational cost [8-10].

2. Cogeneration Plant

The fast depleting energy source is a key factor to use energy efficiently. One of the industrial methods leading to energy efficiency is capturing the flue gas and using the heat to produce steam through boilers and electricity through generators. Effectively capturing the flue gas heat became an interesting study scope by industrial players and academicians since flue gas with high temperatures contains a considerable amount of energy [11-13]. Study shows, waste heat effectively harvested by various technologies rather than energy lost in the industrial process to the environment [14].

The cogeneration plant is one of the industrial facilities that harvest waste heat efficiently. The cogeneration plant is also known as a combined heat and power plant, shown in Figure 1. The cogeneration plant consists of Gas Turbine Generator (GTG) and HRSG. GTG generate electricity and hot exhaust gas at the same time. Meanwhile, HRSG produces steam using the exhaust gas released by GTG. A steam turbine can be added as a back pressure machine for a combined cycle power plant [15]. The general structure of the combined cycle power plant is shown in Figure 2.

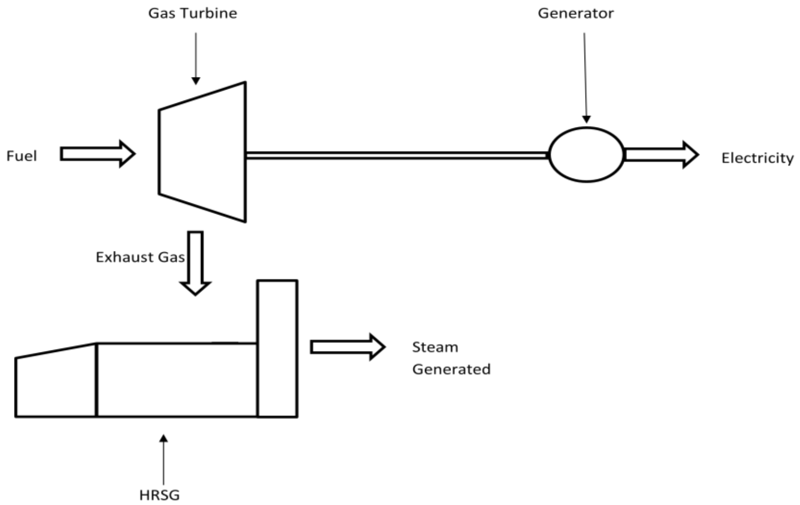

Fig. 1. The general structure of a combined heat and power plant

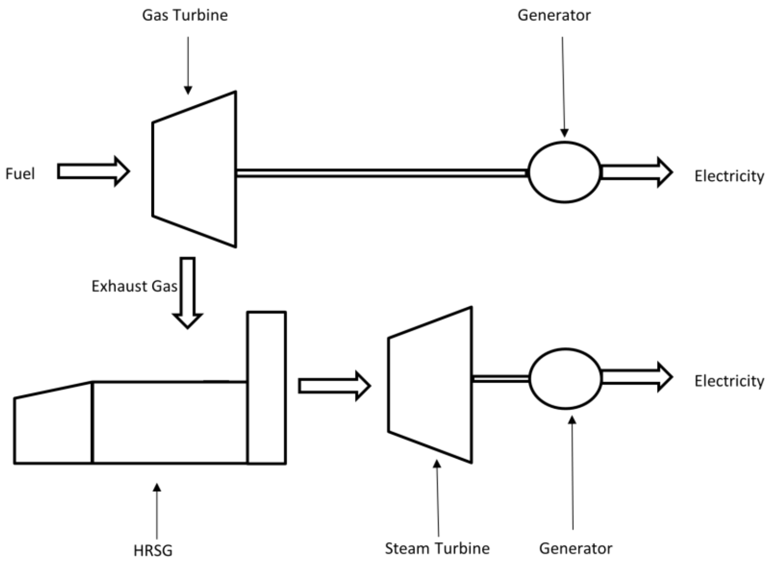

Fig. 2. The general structure of a combined cycle power plant

2.1 Heat Recovery Steam Generator

HRSG is an important plant in both cogeneration plants and combined cycle power plants. The general structure of HRSG is shown in Figure 3. Various parameters were studied with the aim of the optimization of HRSG heat recovery from the gas turbine exhaust. An optimization of HRSG can be done on two levels. The first level optimization area covers operating parameters such as type and number of heating sections, pressure level, steam pressure and steam temperature. The second level covers detailed design components such as type of surface, flow arrangement, gas velocity and geometry dimension of HRSG [16]. Table 1 shows the various study performed to improve the HRSG efficiency.

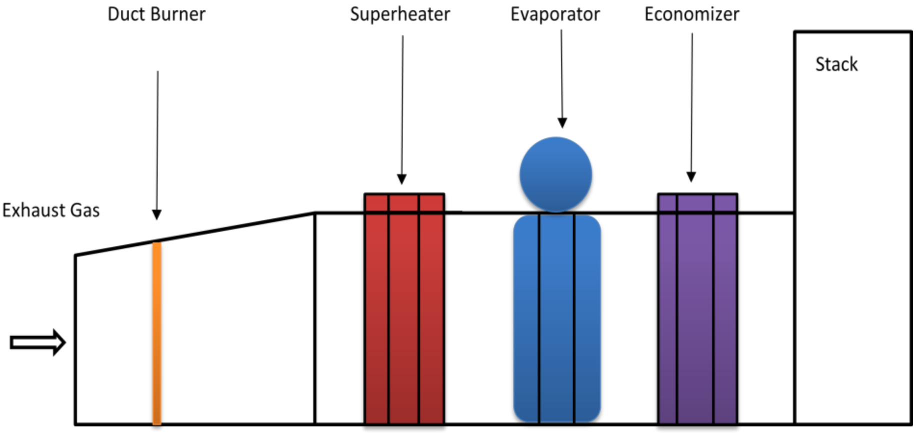

Fig. 3. The general structure of HRSG

Table 1
Various studies on HRSG efficiency

Research topics	Studied parameters	Reference
Experimental analysis of HRSG for simulating internal flow behaviour using Euler and swirl similitudes	HRSG inlet duct flow and HRSG pressure levels	[5]
Exergy analysis of HRSG: Effect of supplementary firing and desuperheater	HRSG velocity profile and pressure drop	[8]
Combined cycle plant efficiency increase based on the optimization of the HRSG operating parameters	Various configurations of HRSG in combined cycle plant	[6]
Thermal design and optimization of a HRSG in a combined cycle power plant by applying Genetic Algorithm	Various configurations of fin-tube in HRSG	[17]
Computational fluid dynamics modelling of high-temperature air combustion in an HRSG	Various fuel nozzle configurations and optimum mass flow rate of fuel	[18]

Operational efficiency in terms of thermodynamic parameters is an important criterion to achieve an improved HRSG efficiency. Flue gas entered to the first entry point in HRSG is the main source of energy towards the steam production in HRSG. The first entry point for HRSG is the inlet duct. The researchers conducted various studies to split the flue gas and reintroduce it at multiple sections of the HRSG to improve steam production. A method to boost the performance of HRSG by split the flue gas at the HRSG inlet to produce a higher amount of steam in the evaporator was identified. The flue gas at the inlet of HRSG is split and introduced in two sections. One at Superheater, which resulted in high-pressure superheater steam, is close to their ideal heat transfer condition. Meanwhile, another flow of the split gas was introduced directly to the evaporator [19]. Flue gas split concepts using two arrangements were conducted using wet recycling and dry recycling. Dry recycling is done after the removal of moisture and water. Meanwhile, wet recycling was done right after the gas exit from HRSG. This two arrangement was studied with the diluted flue gas where the split gas modification resulted in a lower power requirement and a smaller heat transfer area [20].

Besides the flue gas inlet towards HRSG, HRSG configuration with double and triple pressure is able to improve the boiler's efficiency in terms of steam output. A study on HRSG configuration with double pressure and triple pressure on the plant's efficiency found that the increased pressure level of steam generation increased the heat recovery from the flue gas. Therefore, researchers concluded that the overall plant cycle's energy efficiency improved with an increase in the number of pressure levels. The improved efficiency justifies the increase in the investment cost by the author [21]. Economic point of view is an important key area in HRSG design and optimization besides thermodynamic parameters. HRSG optimization is a complex process that involves various parameters. Therefore, research opts for numerical modelling of HRSG to study its optimization. A genetic algorithm model was used to study cost-efficiency repowering steam power plants with HRSG and GTG [7]. Similarly, in another research, a genetic algorithm model was used to optimize the thermal design and minimize the cost of HRSG [17]. The mixed-integer nonlinear programming approach optimized the HRSG heat stream and showed positive results toward HRSG optimization on heat network and maximizing power output [22].

Even though the flue gas is the main source of energy for the HRSG steam production, HRSG operates in fired and unfired mode. HRSG in combined heat power plants is usually fired to accommodate fluctuation in steam demand. The gas turbine's exhaust gas temperature varies from 450°C to 525°C. Gas turbine exhaust gas contains an oxygen content of 12%-15% based on the model of GTG used. Therefore, this oxygen concentration is sufficient for supplementary fuel burning at the HRSG duct burner. Besides that, there is HRSG comes with an additional air blower fan to increase the oxygen concentration. Supplementary firing in the duct burner of HRSG can increase the exhaust gas temperature at a range of 850°C [23]. After supplementary firing, an increase in turbine exhaust gas temperature leads to a rise in the steam output by 65%. Supplementary firing significantly reduced stack temperature and increased superheated steam temperature. The stack temperature acted as an indicator of the efficiency of the HRSG since more heat captured by HRSG lowered the stack temperature. An increase in superheated steam temperature was noticed when increased in inlet gas temperature of HRSG. Meanwhile, reduced stack temperature was seen due to the improved heat transfer in the economizer [24]. From here, we can conclude that the presence of supplementary firing in HRSG increases the exhaust gas temperature and relatively increases the steam output, leading to improved efficiency in HRSG.

Since supplementary firing has been an important factor in HRSG efficiency improvement, the study on duct burners and various fuel types has always been an aim of researchers and industry players. HRSG duct burner configuration was studied in multiple configurations to produce the desired result. The most common design is inclined and grid configuration. In the inclined configuration, the burner head is arranged in ways that flame parallel with exhaust gas and fuel supply pipe. In grid configuration burners, the elements are arranged in series with space in vertical intervals. Fuel manifold pipes are fixed to each burner element. The firing burner fuel feeds into the manifolds and is dispersed through the tip to the HRSG duct burner for supplementary firing [25]. The vast majority of studies about supplementary firing were conducted on a combined cycle power plant. Early days of the study on supplementary firing in combined cycle performance using partial gasification with char, full gasification with coal, and full gasification with syngas concluded supplementary firing did not increase combined cycle efficiency and specific net output in terms of work output per unit of mass of coal. Among the supplementary fuel studied, full gasification with syngas produced the highest work output compared to other fuels as supplementary firing [26]. Meanwhile, recent studies show otherwise. In a biomass-integrated gasification combined cycle power plant, the increase in the supplementary firing rate increased the work output in integrated coal gasification combined cycle power plant for pressure ratio and temperature ratio gas cycle [27]. A similar outcome was concluded in a study on the effect of supplementary firing in HRSG and found that the efficiency of HRSG increases with supplementary firing [8].

2.2 Computational Fluid Dynamic analysis in HRSG

CFD is a cost-effective tool to analyze the fluid flow using a numerical solution without modifying the existing unit [28-37]. Therefore, researchers are keen to utilize CFD modelling to improve HRSG efficiency. Fluid flow, heat transfer and combustion analysis for a typical HRSG application were studied using CFD simulation models. HRSG burner combustion of a CFD can provide an overview of temperature distribution and the concentration of the by-products formed during the combustion. CFD predicted data, able to assist in HRSG optimization.

In a study, high-temperature air combustion in HRSG was investigated using CFD. The simulation showed that fluid velocity magnitude is close to the burners and HRSG boiler inlet side compared to the other part of the boiler. Meanwhile, the low-velocity magnitude in the top section of the boiler caused a dead zone region. Burner vicinity had a higher flame temperature, and lowest Oxygen concentration since most of the oxygen was used for the combustion reaction. The study also found that more NOX was formed closer to the burner due to the high oxygen concentration and temperature. Increased equivalence ratio in the fuel-lean condition leads to high flame temperature and more NOX [38]. The study showed that HRSG efficiency depends on the temperature distribution and oxygen concentration in high-temperature air combustion.

Operation of combined cycle power plant operation and combined heat and power plant influence by the gas turbine operation. On the other hand, gas turbine load fluctuation is based on the power demand. Therefore, various loads from GTG will lead to various exhaust gas flow at the inlet of HRSG. Therefore, researchers studied HRSG with different load and swirl angles with the aid of a CFD model, which was validated using power plant data. The velocity profile for various loads showed a similar velocity profile. With that, it is seen that the load variation does not bring drastic differences towards the efficiency of the HRSG of that particular case study. Meanwhile, the swirl angle showed a higher temperature contour depend on the swirl angle at the inlet. Therefore, the efficiency of HRSG in terms of temperature distribution can be modified according to the swirl angle. This model generally acts as a guide to the power plant operator to understand the gas flow path [39].

The fluctuation in load can lead to fluctuation in GTG exhaust gas temperature. The exhaust gas temperature also depends on the model of the gas turbine used. Therefore, to predict the suitable HRSG tube selection, a study was conducted with an inlet temperature range from 127℃ to 327℃. The study also included artificial heat leakages as an important component where higher heat leakages result in lower energy efficiency. The study concluded that three cylinders with 227℃ and eight cylinders with 127℃ showed the highest efficiency. The optimization study showed that the HRSG efficiency depends not only on the number of tubes present in the HRSG tube bank but also on the inlet exhaust gas temperature. [40]. Therefore, the exhaust gas exit from GTG entering HRSG need to be uniform as possible to achieve higher efficiency. The research was done to ensure uniform velocity and heat distribution. Uniform heat distribution after the perforated plate of a HRSG is crucial to provide uniform heating at the first section of HRSG, which is generally superheater tubes. A study showed that incorporated perforated plate at the inlet channel of HRSG provided a uniform distribution of velocity and temperature. The study also further showed axial velocity profile in the diffuser's outlet section can be improved by increasing the perforated plate's pressure loss coefficient if there are no burners and baffles. Uniformity of axial velocity is important in passes between baffles to attain uniform flame length, and the CFD showed a uniform temperature distribution at the burner [41].

CFD is used as a tool to study the influence of geometrical modification towards the improvements on HRSG efficiency. HRSG tube modelled with different tube bank configurations simulated in CFD to exhibit flow behaviour. The flow velocity depends on the inlet flow and geometry conditions. An increase in the number of tube rows resulted in destroying any velocity component parallel to tube rows. The geometry arrangement of HRSG tubes greatly influence the pressure drop, and it varies from case to case basis. The study also explored finned tubes, resulting in reduced pressure drop with increased pitch length [42]. The influence of flue gas and temperature distribution in whole HRSG was studied using CFD on single angle roof, dual-angle roof and airflow optimized evase. The study revealed a flue gas recirculation region at the upper section of the HRSG duct. Meanwhile, no recirculation was noticed at the optimized airflow model [43]. Geometry modification at inlet duct considered to achieve uniform velocity profile. CFD was used to modify the upper duct wall of 5MW HRSG to optimise flow, and a uniform velocity profile was achieved [44]. Significant problems arise for a supplementary firing if the burner is placed in a non-strategical location in the HRSG duct. The efficient location of supplementary firing in the HRSG duct was studied with three different locations. The burner at the inlet and centre of the HRSG duct produced desired temperature contour. In that particular location, the simulated burner is predicted to operate without generating a high temperature zone since the maximum allowable temperature for the tube is 600°C. The study concluded that the increase in steam temperature from 397°C to 451°C with the burner location and optimized nozzle flow rate lead to a 37% increase in heat transfer [18].

The safety aspect of a HRSG during operation has been an important aspect of past studies. The operational parameters that might lead to failure were studied using CFD. Startup failure in HRSG associated with residual fuel concentration. The transient natural gas ignition failure simulation showed that the exhaust flow rate slowly reduces with time after ignition fails. The CFD showed that the natural gas migrates through HRSG near the ceiling due to the buoyancy effect. After 800s, the only a small trace was found. With that, the researchers concluded, no significant damage was initiated due to the natural gas ignition failure [45]. In a recent study, the efficiency of HRSG in an off-design operation was studied. In that study, the variation of gas turbine flow rate was compared with the base model. The flow gas increase showed an increase in gas temperature along the tube's length, where differential temperature between inlet and exit was reduced compared to the base model. With the decrease of gas flow, the differential temperature increased. On the efficiency side, when flow gas increased, the efficiency is 77%, where the base model is 86% due to abundant hot gas flow, leading to an increase in the temperature at the stack exit. Meanwhile, the study on partial or total plugging of the tube showed low-pressure evaporator had a moderate effect on efficiency, reducing 86% to 83%. A significant effect was noticed on the efficiency at low-pressure economizer, where the efficiency reduced from 86% to 73%. Deviation of the exhaust gas flow into the boiler's zone of low heat transfer showed when gas flow is entirely through the core of the heat exchangers, and the efficiency may increase by as much as 8%. A drop in the efficiency by almost 50% obtained when gas is permeated through the inactive zone of the HRSG [46].

3. Conclusions

In this review article, research done in past years shows that the improvement of the efficiency of power generation boilers is widely studied. There is always a need for new technology to improve power generation boiler efficiency to meet the industrial market demand. Therefore, researchers need to continuously contribute innovative ideas and knowledge to optimize the existing HRSG design and operating conditions. The improvement of boiler efficiency by experimental analysis during operation is not feasible and incurs a higher cost. Therefore, CFD is widely used to replicate the boiler operation and further use the validated model to improve the area. HRSG always operate as an integrated part with GTG. Therefore, GTG operating conditions lead to significant operational stability and efficiency in HRSG. HRSG duct plays a major role in the uniform heat distribution towards the first section of HRSG. The researchers can further study to improve the heat distribution in the HRSG duct. The tube arrangements and improved tube design are other areas not explored much in HRSG related research.

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