

Hydrogen Fired Steam Boilers

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Abstract- With the depleting energy sources such as fossil fuels there is a need to go for renewable type of fuels. More over the increasing concern for the environment has lead to the revolutionary ways of clean fuel utilization. Hence this project provides the solution for the future energy demands employing hydrogen as the energy carrier for the energy requirement.

Through this project with the mode of production of hydrogen it offers flexibility in the actual fuel source for the production of hydrogen. Currently coal being used in the steam boilers the project also considers the coal as fuel source but in future the biomass which possess carbon content in them can later be utilized as the active source of fuel for hydrogen generation through the same gasification technique being employed thus not involving much of changes in plant design in the future (almost nil).

A Hydrogen co-production through synthesis gas formation from coal (primary steam) and high temperature steam electrolysis is employed (secondary steam). The product of combustion of hydrogen in steam boilers along with the steam from the steam drum is used to run the turbines. The outlet steam from the turbines instead of being condensed is used in steam electrolysis for hydrogen production and further the outlet from the electrolysis chamber is passed over the pulverized coal for synthesis gas production.

1. INTRODUCTION

In the today's scenario there is an increasing power demand all around the world. Thus we have both conventional and non-conventional sources of energy. With an increasing demand and depleting fossil fuels there is a more need for the more renewable and clean energy source for the future.

1.1 Objective

This project mainly aims at modifying the existing thermal power plant such that Hydrogen can be used as the fuel in the boilers for steam generation. it also involves in using the used steam for the process steam application for producing hydrogen as well for storing it using metal hydride compressor (through waste heat recovery)

1.2 Motivation

The current thermal plant net efficiency is 32.34% and there is a scope for improving the efficiency by reducing the amount of steam used for auxiliary applications in such as soot blowers, Low pressure heaters, boiler combustion startup, etc... And also with the evolving technology of the use of applications of the bi-products of the syngas gas the dual source can be put to good use both

as in case of electricity production and the supply of chemicals for other industrial benefits.

1.3 Background

Currently an increasing revolutionary ideas are being discussed for the in-situ power production through the coal gas reforming technique where the hydrogen obtained after the water gas-shift reaction are branched out in using it for fuel cell and in gas turbines where the waste heat from the products from the gas turbine can be used for steam generation applications rather than going for direct hydrogen fired steam boilers. One of the advantages that the hydrogen fired steam boilers is the product of the combustion which is the steam (virgin water) it can in turn be used for power production in the turbines. Thus the actual combustion will not lead to heat loss through flue gas let into the atmosphere which is around 147°C in our current cases.

2. DESIGN APPROACH

2.1 Project Description and goals

This project involves in using coal as the primary fuel for hydrogen production through synthesis gas production. Thus the other pollutant contents of the coal such as sulfur, nitrogen, chlorine can be obtained as bi-product in the form of H₂S, COS (3-10%), HCN and HCL. Trace elements associated with both organic and inorganic components of the feedstock, such as mercury and arsenic are released during gasification and partition between the different ash fraction (e.g., fly ash, bottom ash, slag) and gaseous emissions. The particular chemical species and physical forms of condensed-phase and vapor phase trace elements are functions of gasifier design and operating conditions. The synthesis gas is cleaned of these minor and trace components to predetermined levels consistent with further downstream processing. To clean the synthesis gas, chemical and physical solvents such as methyl diethanolamine (MDEA), methanol, etc. operating at near ambient temperatures or lower are employed.[1]

Later the only products being CO₂ and H₂ after the waster gas shift reaction Cellulosic membranes (separation through diffusion since hydrogen has low molecular weight and thus higher rate of diffusion) can be used to separate hydrogen from synthesis gas through continuous, low energy consumption and absence of additives. The CO₂ then can be again circulated back to the coal gasification chamber so that the heat content from the CO₂ can be put into effective use for the gasification process.

The hydrogen thus produced is then stored using the metal hydrides through hydride compressor. A compression cycle can use traditional fuels and can reduce compression energy cost to less than one half of that

required for a mechanical compressor. The hydride compressor is a form of “heat engine” based on the Carnot cycle. Its energy efficiency is about 50% of Carnot efficiency. Carnot efficiency is based on the temperature difference between the hot energy source and the cold heat sink. Waste heat is usually available in the 130°C range. With a 30°C cooling water temperature, Carnot efficiency is almost 25 percent and hydride compressor efficiency is from 14 to 16 percent. Thus since the waste heat is free, cycle economics can endure this level of efficiency. While 15 percent is about 1/2 that for a mechanical compressor, so the hydride compressor will enjoy a 67% lower energy cost. Hydride alloys traditionally used for compressors have been from the “AB₅” family. AB₅ alloys have good capacity, usually storing from 1% to 1.3% hydrogen by weight. They can operate for over a million cycles at temperature from ambient up to a little over 100 °C (130 approx. in this case). When these alloys are cycled at higher temperatures and elevated pressures, their performance can deteriorate through a process termed disproportionation while in this case it is well below the disproportionation temperature. [4]

The waste heat which can be obtained from the used steam from the LPT after losing considerable amount of heat in the Solid Oxide Steam Electrolyser (SOSE) for hydrogen generation.

Thus here the hydrogen later is brunt in the boiler along with oxygen (separated from air using oxygen concentrators) thus providing heat for steam generation. Simultaneously the bi-product of the combustion being steam can be utilized to run the turbines. While only 560 TPH of the steam is admitted later into the IP turbine after the reheating. Thus 140 TPH of the steam is being used for auxiliary applications such as soot blowers, boiler startup, LP heaters, etc... thus in this case of hydrogen fired boilers the need of the soot blowers and boiler startup operation is not necessary thus some amount of the steam is saved. While the need for the first 2 stages of LP heaters is also out of question since the steam from the hydride compressors after losing considerable amount of heat and at 1 atm can be condensed close to 30-95 °C after passing it through a condenser. Thus this process also involves in the production of work output from the product flue gases of the coal gasification technique while is primarily composed of CO₂ and N₂. These products are left to expand in the gas turbine to atmospheric pressure to produce useful work. Later the water heat from the outlet of gas turbine is again used for air preheating of the inlet air (oxygen) for the coal gasifier.

Thus in this closed cycle of power generation the hydrogen utilized for combustion is partially produced from SOEC and partially from the after treatment of the coal and steam in the coal gasifiers. Thus this project involves in developing of the “Development of the hydrogen co-production and hydrogen fired steam generation working cycle for the future of thermal power plants”

2.2 Technical Specification

Table 1 . Technical specifications for the hydrogen fired steam generation cum hydrogen co-production cycle.

Coal Composition
 C = 79.1 /CO₂ =7/ H=5.0/CO =21 /O=6.4 /CH₄ =2.5 /N =1.7H₂=14/H₂O=1.7 Ashes = 9% wt of coal/N₂=53/A=6.1 (180°C)
 H₂O=2.5
 Air: RH =80%
 PSH₂O = 26 mm Hg (25°C, 740 mm Hg)
 Steam is blown in at 30.8psig(gauge pressure) pressure with blast.
 Mean specific heat of ashes = 0.21 Kcal/Kg K (25°C - 180°C range)
 Boiler capacity : 700 Tons
 of Steam/Hour
 ii. Temperature of steam : 540°C
 iii. Pressure of Steam : 137 kg/cm²
 iv. Turbine :
 3 stage turbine
 v. Generation Voltage : 15.75 kV
 vi. Generation Capacity : 210 MW
 Overall cost consumption is = 0.729 Kg per KW hr

2.3 Design Approach

2.3.1 Hydrogen Burning

The biggest problem with burning hydrogen is the combustion velocity (2.65 – 3.25 m/s for hydrogen compared to 0.40 m/s for methane). Thos means that it is difficult to control the flame, as high pressures are required. The jetting on the boiler must be modified and the hydrogen/air mixing closely regulated in order to produce safe and efficient combustion.

Thus a safer way is adopted for producing heat directly from hydrogen by means of a catalytic burner. This method has several advantages over direct hydrogen combustion notably that the combustion temperature can be closely matched to the desired temperature and that flameless combustion is invariably safer than flame combustion. Catalytic burners consist of a porous palladium/platinum plate attached to the hydrogen source. The hydrogen enters the plate, diffuses in the pores and reacts catalytically to produce heat.

We concluded this brief investigation into hydrogen burning by deciding that, should we decide heating the dwelling using hydrogen produced from the electrolyzers, a hydrogen boiler would be the most viable way. Thus the combustion of hydrogen being a major project in itself. (below are the two possible functional setup for catalytic combustion)

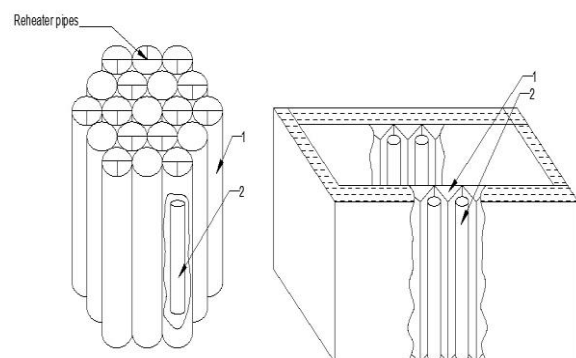


Figure1. Arrangement of the catalytic combustor

Rods of sintered Al_2O_3 are used (1- cylindrical cell , 2-rod) with its pores spaces infiltrated with the platinum black are inserted onto the tubes. The surface of each rod is coated with the fluoroplastic film, which is penetrable to gases and steam. The rod has a diameter of 5.8mm and length of the metal of 6.3mm. it has an axial channel of diameter 1mm. the diameter and the length of the metal tubes have been validated in the preliminary experiments to optimize the combustor design. The re-heater pipes are placed alternatively along with the catalyst pipes so as to carry away the heat and prevent the pipe material from failure. Thus the arrangement of the each individual cells would lead to a larger catalytic combustor.[2]

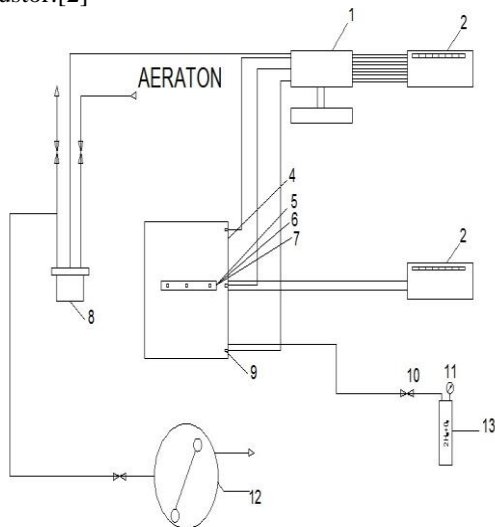


Figure 2. Functional setup

The principle issue is the concern of the feasibility and condition of the ignition of gas – air mixtures by a catalytic surface, thus here we discuss the catalyst for the combustion of a wet donating gas, distinguished mainly by the presence of porous, hydrophobized, fluroplastic (Teflon-type) film, which ensures the efficiency of the catalyst operation in a wet medium. The flameless combustion of the hydrogen on the surface of a hydrophobized catalyst is considered in which the specific rate of combustion of hydrogen and the ignitability of the catalyst surface along with the high temperature vapor medium, its temperature and the pressure.

2.3.2 Generation and utilization of the secondary steam

Steam produced in the boilers as the bi-products of the combustion of the hydrogen in the boilers also contribute in power generation when are allowed to run the steam turbines. With the calculated value it has been found out that 151.3 TPH of the secondary steam is produced. The steam formed through the combustion of hydrogen are mostly in their excited state while soon later they return to ground state thus being most product of the combustion of the fuel is through radiation energy. Thus the steam formed at 1.3 Ksc in the boiler after passing through various levels of the boiler elements such as superheater, reheater and economizer it loses its heat and is later given out from the boiler at 1.3 Ksc and 334°C. hence steam mixing takes

place just before the LPT inlet where the secondary steam is mixed along with the IPT outlet of the steam.

Thus the steam combined runs the LPT turbine giving out 19,201.648 kw of power at this turbine outlet. And also 151.3 TPH of the steam from the boiler is let to contribute with 441.44 TPH of steam from the IPT outlet.

2.3.3 Solid Oxide Steal Elecrolyser

An equal amount of steam as from the combustion product is extracted from the IPT turbine in between the inlet and outlet @3bar and 234.078°C this steam is then admitted into the steam electrolyser which operates at 100°C and with 41% efficiency when considering the whole necessary energy is supplied ad heat and the electricity demanded is from an heat engine. Thus 12.19 TPH of the steam is converted to H_2 and O_2 leaving behind 139.109 TPH of the steam to the Coal Gasification plant.

Thus 8.76% of the hydrogen required for the combustion is got back through the electrolysis technique. Since the SOSE is operating at elevated temperature the over-potentials in the cells is less predominant and hence less power loss.

The electrochemical stack is heated directly (by the supplied steam) or indirectly (through heat transfer) such that the electric energy needed by the process. for water-splitting reaction in the SOSE, the total energy requires $\Delta H(T)$ is the sumof electrical energy demand $\Delta G(T)$ and the thermal energy demand $Q(T)$ i.e., $\Delta H(T) = \Delta G(T) + Q(T)$, where $\Delta G(T)$ is the change in the Gibbs free energy, $Q(T) = T\Delta S(T)$, $\Delta S(T)$ is the change in the entropy, and T is the operating temperature of the SOSE. [3]

More over as the operating temperature of the SOSE increases the Gibbs energy (ΔG) decreases which means the electric power demand reduces, while the function $T\Delta S$ increases while means more energy in terms of the heat is required. Hence it becomes economical since the electricity production costs more and while a part of the electrical energy demand is compensated by the equivalent heat addition.

2.3.4 Semi-Brayton Cycle from the products of the Coal Gasifier

The after products (gaseous) in the cola gasifier is mainly carbon-di-oxide and nitrogen. With the process of the coal gasification being exothermic there is a good opportunity for the availability of the sensible heat for the left over gas. Thus 4836.872KJ of heat is available for per Kg of the coal fed. Thus the available products of the combustion is at 850.25°C and 21.7 bar. Hence this gas is thus allowed to run a gas turbine with its outlet pressure and temperature being 1 atm and 193.091°C respectively.

Thus the work output from the gas turbine being 143058.28 KW. The advantage being no work/compressor work is actually performed in achieveing such high pressure. The steam at the inlet of the gasifier being @3bar and while the coal feed/coal bed initially thus reactant being in solid from thus after reaction the gases formed increases the total number of moles present and hence the partial pressure. Thus resulting in 21.7 bar from 3 bar pressure.

2.4 Constraints, Alternatives and Tradeoffs

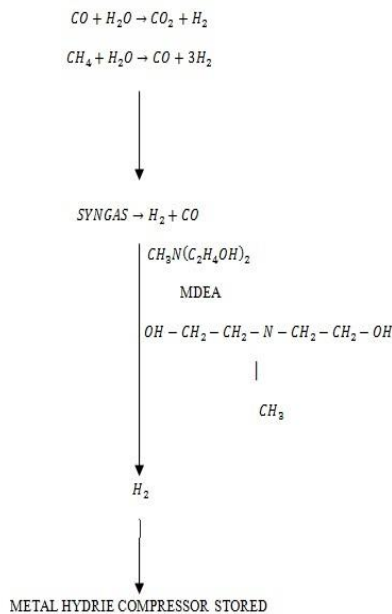
Here in this modified cycle a back pressure is developed right after LPT turbine and thus a replacement of the current condensate turbine is required.

Another constraint would be the coal fed considered in the proposed model is bituminous coal which is a higher grade of coal than used in the present boiler. Thus as when we go for low grade fuels the ash/tar residue is more which would also result in the wastage of heat as being carried by them.

Moreover though this model involves in only removal of the components such as Electro Static Precipitator, chimney, ash handling circuit ID fan (induced draft) and FD fan (forced draft), etc... It also involves addition/installation of new working parts such as SOSE, catalytic burner and metal hydride hydrogen storage system which has capital investment.

Overall modifies plant is less efficient than the existing one by 3% but the net plant output is now increased by 124231.42 KW and thus can provide more electricity for future demand of Course there is also an simultaneous increase in the heat input but we can avoid the possibility of increasing the capacity of the steam drum, replacement of the boiler mountings, etc.. The current boiler's inside operating pressure is higher than atmospheric pressure by 0.27 atm, while the previous mode of operation has negative pressure of - 5mm of H₂O.

2.5 REACTION ON REMOVAL OF HYDROGEN IMPURITIES AND HYDROGEN STORE



3. RESULTS AND DISCUSSION

3.1 Results

Thus mixing of the steam happens between steam from the IPT with 190°C, 1.3 ksc and 441.453 TPH and the

steam from the boiler @334°C, 1.3 ksc and 151.3 TPH before entering the LPT.

The pipeline from the IPT has a diameter of 1m and by considering the area of the cross section of the steam pipe from the boiler as 1/3rd to the area of cross section of the pipeline from the IPT (since mass flow rate is approximately 1/3rd).

We have, d₂=0.5774m (d₂- diameter of the steam pipe from boiler)

Table 1. Steam Properties

Inlet properties of the steam from IPT Density = 0.601 kg/m ³ Velocity = 259.911 m/s C _p = 1.986575 KJ/Kg-K Thermal conductivity=0.032476018W/m-K	Inlet properties of the steam from the boiler Density = 0.4562 kg/m ³ Velocity = 352.028 m/s C _p = 2.033049 KJ/Kg-K Thermal conductivity=0.0471989 W/m-K
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Thus same as in the case of the existing conventional power plants and equivalent mass of the steam is extracted right after the HPT and is let into for the heating in the LP heaters. But in the modified cycle the heat required by the first 2 stages of the LP heaters is not necessary since the used steam @1atm right after the hydride compressors is condensed from to form water at 1 atm and 90°C

Hence 107.26 TPH of steam extracted before the re-heater is taken to increase the water temperature in the stage 3 and stage 4 of the LP heater. Thus the modified cycle gives the total work output of 338565.985 KW while the conventional power plant gives 214334.556 KW. Thus being the modified cycle having efficiency of 30.61% yet the modified cycle has advantages over the current plant cycles in ways such as pollution free, flexibility in the fuel being used, lower auxiliary consumption of power and steam, etc..

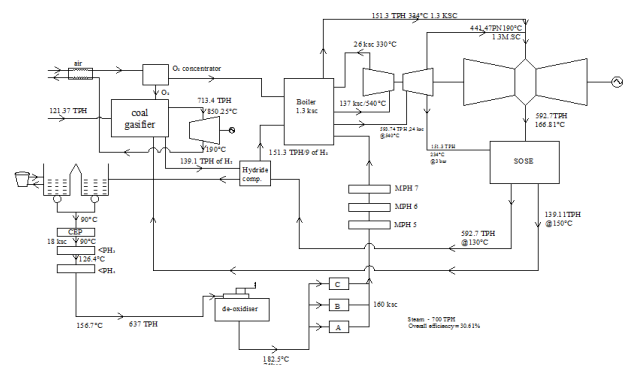


Figure 3. Modified Plant Layout

3.2 Schedule, Tasks and Milestone

There are three major milestone as well as sever smaller tasks that must be achieved in order to reach the milestones. The three milestones are:

- Optimizing the amount of the fuel used and the secondary steam generation
- Employing suitable methods of the co-production of the hydrogen from the used steam in such as SOSE

- Avoiding the amount of waste heat and putting it to proper use such as use of gas turbines, hydride compressor and in solid oxide steam electrolyser.

Thus a proper planning of the processes in order to achieve the above mentioned tasks is required. The efficient use of the available materials and resources play a key role in deciding the feasibility and Eco-friendly project plan.

Thus a group work would provide addition of the human resource as for the success of the project and determining ones key responsibility towards the common goal.

A Gantt chart outlining important tasks and goals can be seen in Appendix A.

Thus,

Efficiency of the proposed model =

$$(338565.985/1106049.814)*100 = 30.61\%$$

Efficiency of the existing model =

$$(214334.556/1106049.814)*100 = 19.37\%$$

4. CONCLUSION

Thus the proposed model of the alternate electricity production via hydrogen as a fuel and also co-production of the hydrogen has an overall efficiency of about 30.61% with coal proves to be feasible for actual power production scenario. It also possesses the following advantages such as removal of the ash handling circuit, ESP, chimney/ID fan, etc... and avoids wastage of steam through soot blowers, Industrial applications of the bi-products of the coal gasifiers. The cost of conversion of coal-fired power plants is a mere fraction of the cost of total dismantling them, or converting them. However it does involve few capital cost for setup such as catalytic combustor, SOSE, and metal hydride compressor/storage system.

It gives flexibility in reaching higher temperature (since no coal clinkers are formed), Emission free, fuel economical and the use of gaseous hydrogen as a coolant for turbines is based on its properties, namely low density, high specific heat, and the highest thermal conductivity (at 0.168 W/(m-K)) of all gases; it is 7-10 times better at cooling than air. Another advantage of hydrogen is its easy detection by hydrogen sensors. A hydrogen-cooled generator can be significantly smaller, and therefore less expensive, than an air cooled one with a working pressure upto 6 bar.

REFERENCES

- [1] H. Watanabe, M. Otaka "Numerical simulation of coal gasification in entrained flow coal gasifier".
- [2] Yu. N. Shebeko, A. V. Trunev, V. A. Shepelin, V. Yu. Navtseva, and A. A. Zaitsev "Flameless combustion of hydrogen on the surface of a hydrophobized catalyst".
- [3] Houcheng Zhang, Shanhe Su, Xiaohang Chen, Guoxing Lin, Jincan Chen "Configuration design and performance optimum analysis of a solar-driven high temperature steam electrolysis system for hydrogen production".
- [4] M. V. Lototsky, V. A. Yartys, B. G. Pollet, R. C. Bowman Jr. "Metal Hydride hydrogen compressors: A review".
- [5] Huai-Jun Lin, Towards easily tunable hydrogen storage via a hydrogen-induced glass-to-glass transition in Mg-based metallic glasses, *Acta Materialia* 120 (2016) 68-74.
- [6] Cagdas Aksu. Extension of PREMIER combustion operation range using split micro pilot fuel injection in a dual fuel natural gas compression ignition engine: A performance-based and visual investigation, *Fuel* 185 (2016) 243-253.
- [7] M. Fischer. Safety Aspects Of Hydrogen Combustion In Hydrogen Energy Systems. *Int. J. Hydrogen Energy*, Vol. 11. No. 9 1986(, Page 593-601).
- [8] Shani Elitzur. Combined energy production and waste management in manned spacecraft utilizing on-demand hydrogen production and fuel cells, *Acta Astronautica* 128 (2016) 580-583.
- [9] David Lewis. Hydrogen and its relationship with nuclear energy. *Progress in Nuclear Energy* 50 (2008) [10] V. K. Verma, Evaluation of the performance of a multi-fuel domestic boiler with respect to the existing European standard and quality labels: Part-1, Elsevier, biomass and bioenergy Volume 35, Issue 1, January 2011, Pages 80-89.
- [10] Satish Sinha, Kankana Das, Chlorine industry: Economics of conversion in India, *Toxics Link*, New Delhi, 2012.
- [11] The Travancore Cochin Chemicals Limited, Annual Report 2011-2012.
- [12] Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Industrial, Commercial, and Institutional Boilers, Policies and Programs Division, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, October 2010.
- [13] K. J. Sreekanth, N. Sudarsan, S. Jayaraj, Achieving Certified Emission Reduction in Rural Domestic Energy Sector Through Alternative Fuel Replacement, *International Journal of Renewable energy research*, Vol. 2, No. 1, 2012.
- [14] K. Hoelzner, A. Szyszka, Operation of 20 kWth gas-fired heating boilers with hydrogen, natural gas and hydrogen / natural gas mixtures, *International Journal of Hydrogen Energy*, Vol. 19, No. 10, 1994.
- [15] Albert E. Avery, Fortifying The Payback Period Method For Alternative Cash Flow Pattern.