Hot Air Gas Turbine Mg2 for electricity production

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1 Abstract

At Stora Enso Fine Paper Nymölla Mill there is a wish to reduce its dependency on external produced electric power. One suggestion that has been made is to install a hot air gas turbine. The purpose of this thesis is to see if it is thermodynamic and economical to go through with the project with the hot air gas turbine. It is of great importance that the boiler-process remains as unchanged as possible.

The effect of higher approach temperature to the turbine has been studied to see the increase of generated electricity.

A total income analysis has been calculated. It takes into consideration how revenue depends on the mixture of fuel, which has to be added for maintenance of existing steam production. Studies of the common gas turbine cycle show that the net work that is being generated is dependent on the admission temperature to the turbine, pressure ratio and work medium. How effectively the heat can be transferred from the flue gas to the air in the gas turbine cycle is of great importance.

By adding heat after the super heater there seems to be an optima about 700 °C. At higher temperature the ratio between increase of generated electric power and sacrifice of fuel is decreasing.

We can establish that a higher admission temperature generates more electric power even if it is more expensive over the optima.

The study clearly shows increasing revenues when the proportion of bio fuel to extra heat addition is increasing.

2 Introduction

2.1 Background

The idea with a hot air turbine application was risen as a part of development work at Stora Enso Fine Paper Nymölla Mill, this to improve their self-sufficiency of electricity. The thought is that through implementation of new heat transferred surfaces in the flue gas channel, warm up combustion air at high pressure, which then expands. The furnace that was used as a base for this thesis is a recovery boiler from Götaverken-Babcock&Wilcox. In this boiler black liquor is used as fuel. Black liquor comes from production of pulp and is a rest after boiling wood chips. In the recovery boiler MgO developes which later absorbs SO_2 from the fluegas. This acid is used at the boiling process of the incoming wood chips. From the furnace you will also get process steam which is used in making paper at the company. This means that the recovery boiler is a central process in making the pulp. This puts specific demands on availability and temperature levels of the process. The temperature of combustion air is directly decisive for characteristic of MgO. Even the slightest

differences in the temperature and the paper being produced will not fulfill the lightness that is wanted.
The problem lays in great deal in the implementation of new components to be able to use available energy levels. In the flue gas channel there are volume limits where installation is possible, which reduces the possibility to take advantage of the energy. The thought is to use existing techniques with a new approach. Since the fuel consists of bio fuel the electricity generation can be considered CO_2 neutral. The absorption of SO_2 in MgOH makes that even this discharge can be reduced. This gives environmental gains compared to combustion of fossil fuels.

2.2 Problem Formulation

The mission is to do a comparable study regarding integration of a gas turbine cycle in existing recovery boiler. The study will include thermodynamic calculations to make a conclusion to see if it is thermodynamically possible. Economical aspects will also be looked at to estimate the economical consequences that an installation would have.

3 Theoretic Feasibility Study

3.1 Gas Turbine Theory

An open gas turbine cycle is being used to convert heat energy into mechanical energy. The gas turbine consists in its simplest form of three main components. These are compressor(C), combustion chamber (CC) and turbine (T) that can bee seen in Figure 1.

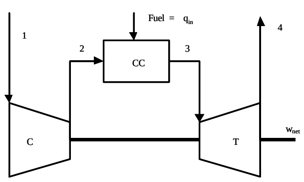

Figure 1: *Gasturbinecycle*

The most common use of an open gas turbine cycle is some sort of combustion of fuel in the combustion chamber. This is absolutely not a must, the energy can be provided via heat exchangers. As a working medium air is often used when it comes to the compressor and flue gas for the turbine with internal consumption in the cycle. To make a simple analysis ideal assumption will be taken.

This ideal cycle is often referred to as the Joule or the Brayton cycle. With index as shown in figure 1 the T-s diagram figure 2 can be drawn.

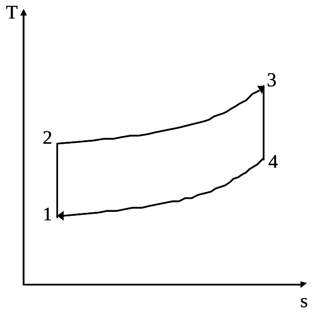

Figure 2: *T-s diagram ideal gasturbinecycle*

The area between the lines in figure 2 is equivalent to the usable work in the cycle. If the working medium is taking the usable work can affected by three parameters:

1) Pressure ratio
2) Approach temperature to the turbine
3) Outlet temperature from the turbine

For isentropic compression and expansion equation 1 is valid.[2]

$$\frac{T_2}{T_1} = p^{\frac{g-1}{g}} = \frac{T_3}{T_4} \qquad (1)$$

This shows the connection between temperature and pressure. When the pressure is increased more compression work power must be add but it gives possibility to receive more useful power from the expander. It is a central matter which power that can be delivered by the cycle, and this can be calculated from equation 2.[2]

$$W_{net} = \dot{m} \cdot c_p \left(\left(T_3 - T_4 \right) - \left(T_2 - T_1 \right) \right) \qquad (2)$$

3.2 Heat Exchanger Theory

Power output from a heat exchanger is calculated according to equation 3.[4]

$$\dot{Q} = k \cdot A \cdot LMTD \qquad (3)$$

By classification of heat exchanger according to current three types of heat exchanger can be discern:

1) Co current
2) Counter current
3) Crossway current

Design principle for a co current heat exchanger can be seen in figure 3 and it's belonging temperature diagram in figure 4.[1]

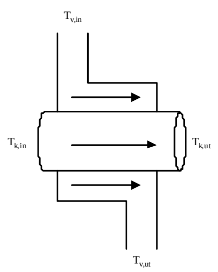

Figure 3: *Design principle of co current heat exchanger*

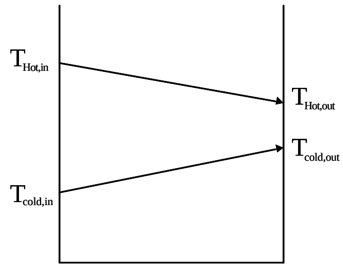

Figure 4: *Temperature diagram co current heat exchanger*

By the way of the connection and temperature diagram it's clear that outgoing temperature of cold medium always will be less then the hot medium outgoing temperature. The logarithmic mean temperature can be calculated by equation 4 [4].

$$LMTD_{cc} = \frac{\left(T_{hot,in} - T_{cold,out} \right) - \left(T_{hot,out} - T_{cold,in} \right)}{\ln \left(\dfrac{T_{hot,in} - T_{cold,in}}{T_{hot,out} - T_{cold,out}} \right)} \qquad (4)$$

Design principle for a current heat exchanger can be seen in figure 5 and its belonging temperature diagram in figure 6.[1]

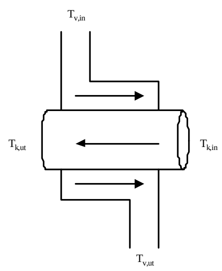

Figure 5: *Design principle of current heat exchanger*

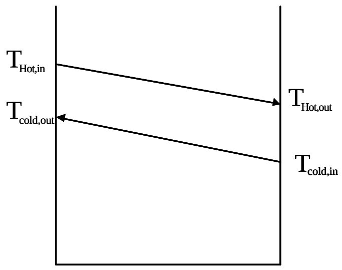

Figure 6: *Temperature diagram current heat exchanger*

Benefit of this design principle is a higher temperature on the cold medium outlet temperature. The logarithmic mean temperature can be calculated by equation 5 [4].

$$LMTD_c = \frac{(T_{hot,in} - T_{cold,in}) - (T_{hot,out} - T_{cold,out})}{\ln\left(\frac{T_{hot,in} - T_{cold,in}}{T_{hot,out} - T_{cold,out}}\right)} \qquad (5)$$

The third type is crossway current heat exchanger. This is a combination of co current and current heat exchanger. Benefit in this type is lower pressure drop since no bend of medium is used in this design principle. The logarithmic mean temperature can be calculated as mean value of co current and current counter heat exchanger as shown in equation 6.[1]

$$LMTD = \frac{LMTD_c + LMTD_{cc}}{2} \qquad (6)$$

4 System studies

4.1 Modulation Of Existing Process

The existing process has been simulated in the heat balance program IPSEpro from Simtech. The flow of air and black liquor will be the constant while the temperature changes when new heat surfaces are being implemented. To be able to keep the heat balance over the components the heat surfaces needs to be fixed in the program. This possibility does not exist in the program. A conjunction of the physical surface in the heat transfer coefficient exists as a parameter in the program. The hts-area and the value for it can be calculated through temperatures for existing process.

4.2 Heat Exchanger Dimensioning

Relation from analyses shows that higher approach temperature to the turbine gives more net work out from the gas turbine cycle. This make that the heat exchangers must been dimensioned after this criteria. Apart from this there are demands on following aspects:

- Ashes must be able to pass through
- Must be easy to sweep

This gives that the arrangement of pipes must be of inline type according to figure 7.

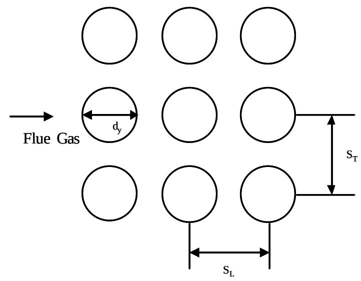

Figure 7: *Inline arrangement*

There are two spaces in the furnace where new heat exchanger can be placed. The space with the highest temperature has a limited volume. This means that this heat exchanger will be the critical one to reach the highest possible temperature. At this simplified study radiation and dirt were not taken in consideration. Heat transfer coefficient for tubes calculates according to equation 7.

$$\frac{1}{k} = \frac{1}{a_{inside}} + \frac{d}{l} + \frac{1}{a_{outside}} \qquad (7)$$

Influence from material in equation 7 considers relatively small and this can be neglected. For calculation of heat transfer coefficient on the airside α_{inside} equation 8 can be used [1].

$$a_{inside} = 7.2(c_{air} r_{air})^{0.79} \left(\frac{0.02}{d_i} \right)^{0.16} \qquad (8)$$

Heat transfer coefficient on flue gas side $\alpha_{outside}$ can be calculated through equation 9.[1]

$$a_{outside} = \frac{l_{fluegas}}{d_h} C \operatorname{Re}^{m}_{fluegas} \Pr^{0.31}_{fluegas} \qquad (9)$$

In equation 9 the constants C and m can be received from tabulated values for different tube arrangement.

Pressure drop in the heat exchanger will depend on losses in the straight tubes and bends. A counter current heat exchanger will give the best heat transfer as discussed earlier. Demand on low-pressure drop in the finite volume makes that this type not can be used. Crossway counter heat exchanger is the most suitable type to be used for this application. Once the heat exchanger has been decided the heat transferable area can be calculated. Through mass flow and temperatures the transferable effect can be calculated through equation 3.

4.3 Simulation After Implement Of Gas Turbine Application

After dimensioning of the heat exchanger as well as the fixation of the htc-area on existing components, a connection between the pressure and the generator effect can be made. Figure 8 show that the optimal pressure is relatively low.

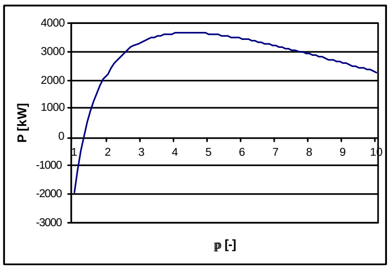

Figure 7: *Dependence between generated electric power and pressure ratio*

4.4 Fuel Addition

According to discussion in section 3.1 the useful work increased by higher approach temperature. This can be made through heat addition by intern combustion before the turbine according to figure 8.

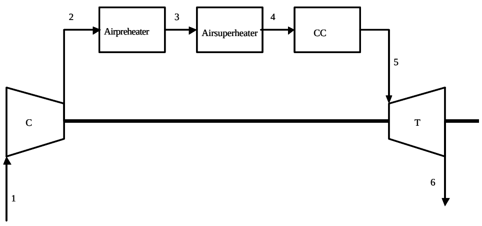

Figure 8: *System with fuel addition*

To analyze the impact of the approach temperature the combustion chamber in figure 8 will be replaced with an ideal heat exchanger. With that increasing mass flow is neglected through the expander. Power from the generator and its relation to admission temperature and pressure ratio can be seen in figure 9.

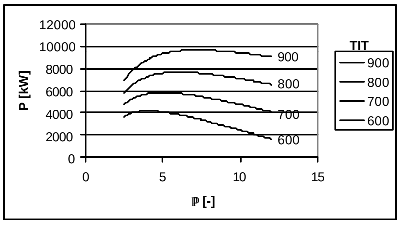

Figure 9: *Power-relation to TIT and pressure ratio*

Since the process puts demand on the outlet temperature from the turbine it means that the pressure must match up with the different turbine inlet(approach) temperature, TIT.

To reach temperature raise some fuel need to be used. By introduce an E-factor as defines according to equation 10, a relation between increase of generated electric power ΔP and sacrificed fuel V.

$$E = \frac{\Delta P}{V} \tag{10}$$

A higher E-factor shows a more effective energy transformation from fuel to electricity. The E-factor is not comparable between different fuels since no consideration between the fuels heat values has been taken.

5 Environmental Aspects

5.1 Bio-fuel

The fuel in the boiler is normally black liquor. Wood chip is the main part of product of pulp. Since black liquor is a remaining product from this production it is bio fuel. The advantage with generating electric power from bio fuel is that CO_2 pollution does not affect the quantity of CO_2 in the atmosphere. Bio fuel is considered as a renewable energy source since it recreates itself in a natural way.

5.2 Renewable Energy Certificate

Electricity that has been generated through renewable energy sources has the right to a renewable energy certificate. This is part of several of ways from the Swedish Government to look for new energy sources. For every generated MWh electricity a renewable energy certificate is issued which can be sold on the market. The electricity consumers are forced to buy a certain share of the certifications per used MWh electricity. This share will increase from 7.4% (2003) to 16.9% in year 2010. The consumers that has not reached their quota will be forced to pay a penalty that is based on last years renewable energy certificate price.[3]

6 Economic Analysis

To make a correct economical analysis additional studies with complete dimensioning of the components are needed. Since this has not been made this study cannot make a complete analysis.

6.1 Revenue Analysis For Gas Turbine Application

In this analysis no consideration on the effect outside the Mg2 furnace has been taken. The fuel that is being burned is only bio fuel, which gives the right to have a renewable energy certificate issued. The income will therefore depend on the electricity price and also on what price the renewable energy certificate can be sold for. Since the use of renewable energy certificate started on 2003-05-01 and therefore is a new phenomenon there is no way that a conclusion can be made as to what kind of income it will be generating. Even the electricity price is hard to estimate.

6.2 Total Revenue Analysis

If you see to the total energy system the existing steam flow will decrease when the hot air gas turbine is installed. To maintain the steam flow it is necessary to add more heat in one of the other boiler. Today the steam expands in existing steam turbines. When the hot air gas turbine is installed this will affect the share of renewable energy certificate and the costs for the CO_2 taxes. The mix of fossil and bio fuel to maintain the existing steam production will be conclusive for the profitability.

7 Conclusions

Studies of literature have shown that the useful work, which is generated by the gas turbine cycle, is dependent on approach temperature to the turbine (TIT), pressure ratio and working medium. Working medium is air and with that there is only the other two parameters to change. How effectively heat transfer in the warmest heat exchanger can occur between flue gas and air is of central matter. By the study it is shown that this heat exchanger should be a crossway heat exchanger.

A possibility that has been investigated is heat addition by combustion before the turbine. In line with the literature study it clearly shows that the useful net work increases with increasing TIT.
E-factor introduces as a measurement of the increase of useful work related to added volume fuel.
A revenue analysis has been made for the hot air gas turbine application. Different scenarios have been made up and the revenue is dependent on estimation of future prices and energy politics.

Installation of hot air gas turbine in the Mg2 boiler will increase the heat transportation from the flue gas. This will cause decrease in steam generation. To compensate this more fuel must been burnt in some of the existing boilers. Total revenue analyses shows dependence between chosen mixture of fuel and total revenue. With increasing share of bio fuel the revenue increasing.

Finally we can say that the project is thermodynamic viable. Calculation shows that it is possible to generate electric power. Whether the project is economic viable or not we have not been able to draw any conclusions. Mainly because lack of information on component prices no economic conclusions can be made.

8 References

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