Paper production project

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Summary

The aims of the report are to investigate the desired air molar flowrate to sustain desirable condition of molar fraction of oxygen in product stream (5%) with determined complete combustion of fuel with $N_{fuel} = 200\ kmol/h$ and the effective heat that can be released after combustion. The airflow is $N_{air} = 2657.8\ kmol/h$ and $Q_{ef} = 1.358 \cdot 10^8\ kJ/h$.

The system of the conversion of heat to the boiled superheated steam is stated as a method of application of energy received.

The second part of the report is aimed at the analysis of the possible transition from the fuel to the in-house produced biomass. The main advantage is independence from the external supply. However, the operational costs, flexibility to crisis and external demand may be critical point to not support the change.

Introduction

Within a paper mill, superheated steam is to be generated via the burning of a hydrocarbon fuel in a combustion unit. The fuel is fed continuously, together with air, into the combustion unit, both the fuel and air enter the unit at $T_1 = 25°C$. The fuel has a flowrate of $N_{fuel} = 200\ kmol/h$ and contains 95 $mol\%$ methane and 5 $mol\%$ ethane. After combustion, the flue gases contain 5 $mol\%$ oxygen; the flue gases exit at $T_2 = 480°C$.

This report is aimed on determination of the required air supply for the combustion unit, the heat released from the combustion, and analyze how the energy will be transformed in ___ process (Problem 1). The second aim of the report is to propose the SWOT analysis for the transition from the gas fuel to the in-house produced biomass combustion (Problem 2).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (1)$$

$$C_2H_6 + \frac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O \quad (2)$$

Results & Discussion

Problem 1: The Energy Release

All calculations must be done only after the thermodynamic model is considered, which is formed from the assumptions made. Assumptions presented in table 1.

Assumptions

Table 1 Assumptions

Assumption	**Reason to consider**
The ideal gas behavior	The thermodynamic properties of the gases that are provided in the task are provided for the ideal gas model, cause not enough values are given for Van-der-Waals models
Argon obeys the CO_2 thermodynamic properties	The heat absorbed by the part of the air must be approximated. The Argon is monoatomic gas, hence, approximation of thermodynamic behavior of Argon as Carbon dioxide gives the overestimation. Due to tiny amount of argon in sample, the assumption will give overestimation in range of uncertainties, which makes this assumption valuable.
Complete combustion of fuel	No carbon monoxide is formed, hence, the thermodynamic expansion is calculated only for the carbon dioxide
Water is gaseos right after the reaction	The model will allow to consider only gaseous expansion of the water, which is the main energy consumer during the 455°C temperature expansion.

Calculations

Air supply

From the equations of combustion (1 and 2), the table 3 can be obtain. Table 3 is showing the change of the molar amount of the gases entering the reaction unit, assuming that amount of air is x moles. The molar ration of air is taken from the Chemical Engineering Tripos Handbook (3), presented in table 2:

Table 2 Molar Air Composition

$\boldsymbol{Gas}$	$\boldsymbol{Molar\ Fraction}$
N_2	78.1%
O_2	21.0%
Ar	0.9%

Table 3 Gas ICE composition

$\boldsymbol{Component}$	$\boldsymbol{Moles, before\ unit}$	$\boldsymbol{Moles, after\ unit}$
N_2	$0.781 \cdot x$	$0.781 \cdot x$
O_2	$0.210 \cdot x$	$0.210 \cdot x - 380 - 35$
Ar	$0.009 \cdot x$	$0.009 \cdot x$
CH_4	190	0
C_2H_6	10	0
H_2O	0	$380 + 30$
CO_2	0	$190 + 20$

From the information that molar fraction of oxygen is 5%, $x = 2657.8\ kmol/h$.

Heat from the fuel

C_p is used at constant pressure, which is not true due to change in moles between reagents and products from table 3. Therefore, C_v should be used. Due to assumption of the ideal gas behavior, the equation A can be used to calculate the C_v:

$$C_v = C_p - R = a + bT - R = a' + bT$$

Where $a' = a - R$.

The total energy released can be calculated by the multiplication of the molar enthalpy of combustion by moles of fuel. Values from the Perry's chemical engineering Handbook (2) are following:

$$\Delta H_{CH_4}^{Comb} = -802.6 \frac{kJ}{mol}$$

$$H_{C_2H_6}^{Comb} = -1428.6 \frac{kJ}{mol}$$

The energy lost by absorption by gas expansion can be calculated via integration of C_v with respect to T.

$$Q_{abs} = \int_{T_1}^{T_2} C_v dT = \int_{T_1}^{T_2} (a' + bT)dT = a'(T_2 - T_1) + b\left(\frac{T_2^2}{2} - \frac{T_1^2}{2}\right)$$

The table 4 contains all the values calculated:

Table 4 Energy Properties Calculated

Physical property	***Value, kJ/h***
$Q_{rel,total}$	$1.668 \cdot 10^8$
Q_{abs,H_2O}	$3.477 \cdot 10^6$
Q_{abs,CO_2}	$5.194 \cdot 10^6$
Q_{abs,N_2}	$2.080 \cdot 10^7$
Q_{abs,O_2}	$1.493 \cdot 10^6$
$Q_{abs,total}$	$3.096 \cdot 10^7$

The effective heat is the energy that can be extracted from the fuel combustion to apply work to surroundings which can be calculated as heat released without heat absorbed.

$$Q_{ef} = Q_{rel,total} - Q_{abs,total} = 1.358 \cdot 10^8 \ kJ/h$$

$$\eta = 1 - \frac{Q_{abs,total}}{Q_{rel,total}} = 0.8143 = 81.43\%$$

Applications of superheated steam

The main source of information is paper by Austin (1).

The paper by Austin on energy use in board and newsprint machines shows that the dryer section is the dominant steam consumer (about 80% of total papermaking energy). Within the paper production line, the main steam users are:

1) **Multi-cylinder dryer section (main sheet dryer).**

   For the newsprint machine the dryer steam is supplied as slightly superheated steam at about

$$p \approx 3.5\,bar, T \approx 156°C,$$

   Which is $18°C$ above the saturation temperature at that pressure.

2) **Dryer hood air-heating coils.**

   Fresh air to the hood is heated by heat exchange with moist exhaust air and by steam coils. These coils are normally on the same steam header as the cylinders, so the hood also effectively utilises the superheated dryer steam.

3) **Condensate return and heat-recovery equipment.**

   Condensing the superheated steam inside the cylinders heats the shell and, via condensate recovery and flash steam, preheats boiler feedwater and other process streams. In what follows we focus on the dominant use: drying the sheet from 50% to 8% moisture in the multi-cylinder dryer using superheated steam.

Conversion of Combustion Heat into supersteam

A heat-flow path from the combustion zone to the cylinders is:

1) **Combustion in the boiler furnace**

   Chemical energy in the fuel released as hot flue gases at high temperatures.

2) **Economiser and feedwater heating**

   Part of the flue-gas sensible heat is recovered in an economiser to preheat boiler feedwater.

3) Evaporator (steam drum and waterwall)

The main heat-transfer surfaces boil the feedwater at the boiler pressure (here about 3.5 bar), generating saturated steam at $T_{sat}\sim 138°C$.

4) Superheater

Downstream flue-gas heat is used in superheater tubes to raise the steam temperature from T_{sat} to the dryer-header temperature of about $156°C$ ($\sim 18°C$ above satuaration). This:

- prevents condensation in long steam lines,
- reduces the risk of water hammer and uneven heat transfer inside the cylinders,
- ensures that condensation, and therefore release of latent heat, occurs predominantly at the cylinder inner surface where it is useful for drying.

5) Cylinder drying and hood heating

The superheated steam enters the cylinder banks and condenses on the inner shell. Condensate and any flash steam are collected and returned to the boiler plant. Part of the same steam supply is used in coils to heat hood supply air, improving evaporation of moisture into the hood atmosphere and allowing optimisation of exhaust humidity and zero-level pressures.

This sequence shows how the heat released during combustion is converted, via a boiler and superheater, into a controlled flow of slightly superheated steam at about $3.5\ bar$ and $156\ °C$, sufficient to dry the sheet from 50% to 8% moisture at a steam demand of roughly $1.7\ t$ of superheated per tonne of paper produced (supported by calculations in appendices)

Problem 2: Alternative Energy Source

The SWOT table (table 5) and following explanations are provided for the swap from the gas fuel to the biomass fuel production.

Strengths	**Weaknesses**
1. Independence of the external supply 2. No new carbon introduction to the biosphere	1. Inflexibility to external demand 2. Inadequacy of the expenses 3. Biological vulnerability of the fuel
Opportunities	**Threats**
1. Recruiting investments due to net-zero policy 2. Governmental support 3. Use of bioproducts as an additional power source or selling unit	1. Decreased volatility of the factory as an asset 2. Low rate of return on the project 3. Air pollution risk.

Strengths

Independence of the external supply

The cost of the product becomes more predictable despite market volatilities and fluctuations of cost of natural gas. Hence, the annual planning becomes steadier, and business becomes more long-term predictable.

No new carbon introduction to the biosphere

Biomass is achieved from sugars, oxygen and ammonia, which are totally natural ingredients. The combustion of the sugar-based biomass will be an analogue of the production of CO_2 by the animals after consumption of sugars; hence, the biosphere has no external carbon added (fuels as gas or oil are predominantly isolated from the biosphere and barely involved in carbon cycle)

Weaknesses

Inflexibility to external demand

The biomass production cannot be increased instantly, hence, if the production is to be scaled up, the limiting factor will be the adaptation of the biomass to grow in larger quantities, which will limit energy supply for a period of time. On the other hand, if the demand is plummeted, the expenses to sustain the same amount of biomass will be inadequate to the production powers. Moreover, biomass is barely conservable unlike the gas, hence, if the demand is too low, the biomass fuel will be wasted due to no use.

Inadequacy of the expenses

During the renovation paper mill cannot work in full capacities, hence, not only using money for renovation, but also losing money from plummeted rate of production. The financial stress may be enormously high, which could damage the company in long term if not handled efficiently. Moreover, the modification should take as little time as possible to shorten the time span of regeneration of the profitability of the paper mill.

Biological vulnerability of the fuel

Assuming that the biomass behaves similarly as the septic tank, any misconduct in use requires long time to recover to previous quantities of the production of biomass. Hence, the sensitivity to impurities in feed, temperature range, contamination by other bacteria is very high, which increases operational recovery cost (if assumed to happen even seldomly).

Opportunities

Recruiting investments due to net-zero policy

Currently many investors look for the business to be sustainable over time to not be assigned to possible governmental obligatory renovation programs. Hence, transparent sustainable and environmentally friendly energy production is a green flag for investors who aim on long term growth of the business.

Governmental support

UK is concerned about the reduction of carbon footprint and may incentivise companies to extend their renewable sources of energy in exchange for limiting the tax pressure. The lobbying of such laws may benefit as a competitive advantage on market as long as most of the work is done beforehand the requirements of the government.

Use of bioproducts as an additional power source or selling unit

Many biomass can be harvested both aerobicly and anaerobicly. Anaerobic process provides production of alcohols from sugars as a byproduct of anaerobic oxidation process of bacteria. Produced alcohols can be distilled and used as a storred source of fuel as a buffer mechanism. Otherwise, if distillation is too complex to introduce, the unpurified alcohol can be sold as a precursor to distillers, maximising the profit.

Threats

Decreased volatility of the factory as an asset

The rearrangement of the factory to be powered by the biomass will require a lot of investment which will take a long time to be covered by profits. The factory for the first few years may be enormously unprofitable, which may lower investments and make factory cheaper on a market, hence, harder to sustain investment rate to the construction of new recycling powers and stations.

Low rate of return on the project

Many sustainable sources of energy are effective only on large scales (as hydroelectrostations). The rate of return for small-scaled renewable source of energy may be undeniably low (i.e. Thirty years) which may not be threat to the competitiveness of the paper mill in the long term.

Air pollution risk

Combustion of nitrogen-containing biomass will emit sensible amount of nitrogen oxides (NO, NO_2), which are strictly banned from the free emission. The regulatory reglaments require to install and administrate the filtration systems, which are increasing the utility cost of the paper production via biomass fuel, increasing the financial return point.

Conclusions

The required molar flowrate of the air to the combustion unit is $N_{air} = 2657.8\ kmol/h$ to the required condition of molar concentration of oxygen in products of 5%. The heat released that can be directly used to boil the water is $1.358 \cdot 10^8 kJ/h$. The heat is transferred to the superheated steam via system of evaporators, superheaters, and hoods.

The SWOT analysis shows that the main advantages are in the field of independence from the external supply. However, the operational costs, flexibility to crisis and external demand may be critical point to not support the change.

Nomenclature & References

Bibliography

1. Austin PC, Mack J, McEwan M, Afshar P, Brown M, Maciejowski J. Improved Energy Efficiency in Paper Making Through Reducing Dryer Steam Consumption Using Advanced Process Control. Scientific Repository (Petra Christian University). 2011 Dec 1;

2. Green DW, Southard MZ. Perry's chemical engineers' handbook. 9th ed. New York, Ny: Mcgraw-Hill Education; 2019.

3. Chemical Engineering and Biotechnology Tripos Data Book. 1st ed. Cambridge press;

Appendix

The example calculation for the Problem 1:

$$Q_{abs,H_2O} = \int_{273+25}^{273+480} C_v dT = \int_{298}^{753} [(29.64 - 8.31) + 0.0124 \cdot T] dT =$$

$$= 21.33(753 - 298) + 0.0124\left(\frac{753^2}{2} - \frac{298^2}{2}\right) = 5.194 \cdot 10^6\ kJ/h$$

$$Q_{rel,total} = -\left(\Delta H_{met}^{comb}\right) \cdot N_{fuel} \cdot 0.95 - \left(\Delta H_{ethane}^{comb}\right) \cdot N_{fuel} \cdot 0.05 = 1.668 \cdot 10^8 kJ/h$$

"Back of the envelope calculation"

Assume the latent heat of evaporation of water at the relevant pressure is

$h_{fg} \approx 2.3 \cdot 10^6\ J/kg$. (2)

The useful heat needed in the dryer per tonne of paper is then

$$Q_{evap} = m_{evap} \cdot h_{fg} \approx 0.8405 \cdot 10^3\ kg \cdot 2.3 \cdot 10^6\ J/kg \approx 1.9 \cdot 10^9\ J \approx 1.9\ GJ.$$

Because the dryer is only about 50% efficient, the heat that must be delivered in the steam is

$$Q_{steam} = Q_{evap}/\eta_{dryer} \approx 1.9\ GJ\ /\ 0.49 \approx 4.0\ GJ/t\ paper$$

which corresponds to roughly 1.7 t of saturated-equivalent steam per tonne of paper.