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Waste heat availability in the raw meal department of a cement plant

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ABSTRACT

The main aim of this study was to determine the available heat in the cement kiln exhaust gas subject to different process conditions. A Norwegian cement plant producing about 1.3 million tons of cement per year was used as a case study. A mass and energy balance was made for the raw meal department, and process data available from the plant process database as well as manually measured gas flow rates were used to calculate the available heat. The available heat can be utilized by a combination of low pressure (LP) steam generation and hot water generation. It was found that waste heat is 1.5–4.2 MW for LP steam generation and 2.2–5.8 MW for hot water generation. The variation in available heat is due to different raw meal types being produced, requiring different gas inlet temperatures to raw meal mill. In cases when no raw meal is produced (in maintenance shutdown periods), all the gas will bypass the mill, and approximately 20 MW of LP steam and 6 MW of hot water can be generated. The heat loss from the system was estimated based on measurements, and the fan power inputs were calculated. Both were found to be negligible compared to the available heat. Furthermore, the total false air coming into the system was estimated as 40–50% of the total gas flow rate going out from the raw meal department.

Nomenclature

Abbreviations

A	Atmospheric air
BP	Bypass
CS	Coarse separator
F	Gas cleaning equipment (Electro-static precipitator and Bag filter)
FF	Filter fan
FSA	Full screen analyzer
G	Gas
GS	Gas separation point
HGF	Hot gas fan
LP	Low-pressure (steam)
M	AFM motor
MF	Main fan
RM	Raw material

Roman Symbols

A_{sur}	Surface area of the pipelines and equipment $[m^2]$
$C_{Dust,\ in}$	Concentration of dust in the inlet gas stream coming into the raw meal department $[\frac{g}{Nm^3}]$

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$C_{p,A}(T)$ Specific heat capacity of the atmospheric air[1] $\left[\frac{J}{kg\cdot K}\right]$
$C_{p,G}(T)$ Specific heat capacity of the gas1 $\left[\frac{J}{kg\cdot K}\right]$
$C_{p,RM}(T)$ Specific heat capacity of the raw materials1 $\left[\frac{J}{kg\cdot K}\right]$
D Diameters of the circular gas pipelines $[m]$
$Dust_{AFM,\ in}$ Mass flow rate of dust in the gas stream which is sent to the aero-fall mill (AFM) $\left[\frac{kg}{s}\right]$
$Dust_{AFM,\ out}$ Mass flow rate of dust of the gas stream that coming out from the cyclone system $\left[\frac{kg}{s}\right]$
$Dust_{BP}$ Mass flow rate of dust of the gas stream that going with the bypass gas stream $\left[\frac{kg}{s}\right]$
$Dust_{F,\ in}$ Mass flow rate of dust of the gas stream which is sent to the ESP (BF) $\left[\frac{kg}{s}\right]$
$Dust_{in}$ Mass flow rate of dust in the inlet gas stream coming into the raw meal department $\left[\frac{kg}{s}\right]$
$Dust_{out}$ Mass flow rate of dust of the gas stream which is going out from the raw meal department $\left[\frac{kg}{s}\right]$
$h_s(T)$ Total specific enthalpy of steam $\left[\frac{MJ}{kg}\right]$
L Latent heat of evaporation of water $\left[\frac{J}{kg}\right]$
M_{wA} Molecular weight of atmospheric air $\left[\frac{kg}{mol}\right]$
M_{wG} Molecular weight of gas $\left[\frac{kg}{mol}\right]$
M_{wH_2O} Molecular weight of moisture (water) $\left[\frac{kg}{mol}\right]$
$\dot{m}_{A,\ AFM in}$ Mass flow rate of the false atmospheric air stream coming into the AFM via the raw material entrance opening $\left[\frac{kg}{s}\right]$
$\dot{m}_{A,\ F in}$ Mass flow rate of the false atmospheric air stream coming into the BF and ESP $\left[\frac{kg}{s}\right]$
$\dot{m}_{BF,\ out}$ Mass flow rate of filtered raw meal powder that coming out from the BF $\left[\frac{kg}{s}\right]$
$\dot{m}_{CS,out}$ Total mass flow rate of the crushed raw meal powder that coming out from the coarse separator $\left[\frac{kg}{s}\right]$
$\dot{m}_{Cyclone,\ out}$ Total mass flow rate of the crushed raw meal powder that coming out from the cyclone system $\left[\frac{kg}{s}\right]$
$\dot{m}_{ESP,\ out}$ Mass flow rate of filtered raw meal powder that coming out from the ESP
$\dot{m}_{G,\ AFM in}$ Mass flow rate of the gas stream which is sent to the AFM[2] $\left[\frac{kg}{s}\right]$
$\dot{m}_{G,\ AFM out}$ Mass flow rate of the gas stream coming out from AFM, coarse separator, and the cyclone system[2] $\left[\frac{kg}{s}\right]$
$\dot{m}_{G,\ BP}$ Mass flow rate of the gas stream which is bypassed the raw meal department[2] $\left[\frac{kg}{s}\right]$
$\dot{m}_{G,\ F,\ in}$ Mass flow rate of the mixed gas stream which is sent to the ESP and BF (bypass gas stream + gas stream coming from the raw meal department) [2] $\left[\frac{kg}{s}\right]$
$\dot{m}_{G,\ in}$ Mass flow rate of the gas stream coming into the raw meal department[2] $\left[\frac{kg}{s}\right]$
$\dot{m}_{G,\ out}$ Mass flow rate of the gas stream which is coming out from the ESP and BF and released to the atmosphere[2] $\left[\frac{kg}{s}\right]$
$\dot{m}_{H_2O}$ Mass flow rate of hot water generated $\left[\frac{kg}{s}\right]$
$\dot{m}_{H_2O,\ in}$ Water/moisture mass flow rate of the gas stream which is coming into the raw meal department $\left[\frac{kg}{s}\right]$
$\dot{m}_{RM,\ in}$ Total raw material mass flow rate coming into the AFM (limestone + additives) – Defined as moisture content inclusive $\left[\frac{kg}{s}\right]$
$\dot{m}_{steam}$ Mass flow rate of LP steam generated $\left[\frac{kg}{s}\right]$
P Pressure in the control volume $[Pa]$
P_{BP} Gauge pressure inside the bypass gas stream $[mbar]$
P_{FF} Power input from the filter fan $[kW]$
P_{HGF} Power input from the hot gas fan $[kW]$
P_M Motor power input to the AFM $[MW]$
P_{MF} Power input from the main fan $[kW]$
P_N Normal gas pressure $[Pa]$
Q Available heat $[MW]$
Q_{HW} Available heat for hot water generation $[MW]$
Q_{LP} Available heat for LP steam generation $[MW]$
$Q_{loss,\ AFM}$ Heat loss at the AFM [W]
$Q_{loss,\ AFM to Cyclones}$ Heat loss at the ducts from AFM to cyclone system including heat losses from the surfaces of coarse separator and cyclones [W]
$Q_{loss,\ after Cyclones}$ Heat loss at the ducts going out from the cyclone system along with the heat loss from the main fan [W]
$Q_{loss,\ before AFM}$ Heat loss of the gas stream from the ducts before entering to the AFM [W]
$Q_{loss,\ bypass duct}$ Heat loss at the bypass duct [W]
$Q_{loss,\ ESP\&BF}$ Heat loss from the surfaces of ESP and BF [W]
$Q_{loss,\ inlet duct}$ Heat loss at the inlet gas duct and hot gas fan [W]
$Q_{loss,\ mixed gas duct}$ Heat loss at the duct after the bypass and gas stream coming from the cyclone mixed [W]
$T_{A,\ in}$ Atmospheric air temperature $[°C]$
$T_{G,\ AFM in}$ Temperature of the gas stream which is sent to the AFM $[°C]$
$T_{G,\ AFM out}$ Temperature of the gas stream coming out from AFM, coarse separator, and the cyclone system $[°C]$
$T_{G,\ BP}$ Temperature of the gas stream which is bypassed the raw meal department $[°C]$
$T_{G,\ F,\ in}$ Temperature of the mixed gas stream which is sent to the ESP and BF (bypass gas stream + gas stream coming from the

1 T indicates that the parameter is a function of temperature.
2 The flow rate includes the dust suspended in the gas.

raw meal department) $[°C]$
$T_{G,\ in}$ Gas temperature which is coming from the preheater tower $[°C]$
$T_{G,\ out}$ Temperature of the gas stream which is coming out from the ESP and BF and released to the atmosphere $[°C]$
$T_{HW,\ in}$ Inlet temperature of the water used to generate hot water $[°C]$
$T_{HW,\ out}$ Temperature of the hot water generated $[°C]$
T_N Normal temperature $[K]$
T_{ref0} Reference temperature (0 °C) $[°C]$
T_{ref1} End temperature 1 (130 °C) $[°C]$
T_{ref2} End temperature 2 (50 °C) $[°C]$
$T_{RM,\ in}$ Raw material temperature which is coming into the raw meal department $[°C]$
$T_{RM,\ out}$ Temperature of the raw material stream which is coming out from the coarse separator and the cyclone system $[°C]$
T_{sur} Surface temperature of the pipelines and the equipment $[°C]$
U Average overall heat transfer coefficient from surfaces to air $[W/(m^2 \cdot K)]$
$\dot{V}_{A,\ AFMin}$ Volumetric flow rate of the false atmospheric air stream coming into the AFM via the raw material entrance opening $\left[\frac{Nm^3}{s}\right]$
$\dot{V}_{A,\ Fin}$ Volumetric flow rate of the false atmospheric air stream coming into the ESP and BF $\left[\frac{Nm^3}{s}\right]$
$\dot{V}_{G,AFM\ in}$ Volumetric flow rate of the gas stream which is sent to the AFM $\left[\frac{Nm^3}{s}\right]$
$\dot{V}_{G,\ AFM\ out}$ Volumetric flow rate of the gas stream coming out from AFM, coarse separator, and the cyclone system $\left[\frac{Nm^3}{s}\right]$
$\dot{V}_{G,\ BP}$ Volumetric flow rate of the gas stream which is bypassed the raw meal department $\left[\frac{Nm^3}{s}\right]$
$\dot{V}_{G,\ F,\ in}$ Volumetric flow rate of the mixed gas stream which is sent to the ESP and BF (bypass gas stream + gas stream coming from the raw meal department) $\left[\frac{Nm^3}{s}\right]$
$\dot{V}_{G,\ in}$ Volumetric flow rate of the gas stream coming into the raw meal department $\left[\frac{Nm^3}{s}\right]$
$\dot{V}_{G,\ out}$ Volumetric flow rate of the gas stream which is coming out from the ESP and BF and released to the atmosphere $\left[\frac{Nm^3}{s}\right]$
$v_{G,\ AFMin}$ Average velocity of the gas stream which is sent through to the AFM $\left[\frac{m}{s}\right]$
$v_{G,\ BP}$ Average velocity of the gas stream which is bypassed the raw meal department $\left[\frac{m}{s}\right]$
$v_{G,\ in}$ Average velocity of the gas stream coming from the preheater tower $\left[\frac{m}{s}\right]$
$x_{H_2O,\ RM,\ in}$ Total moisture mass fraction of all the raw materials coming into the AFM (limestone + additives) $[-]$
$x_{H_2O,\ RM,\ out}$ Total moisture mass fraction of the all crushed raw meal powder that coming out from the coarse separator and the cyclone system $[-]$
$y_{H_2O,\ A,\ in}$ Moisture volume fraction of the atmospheric air $[-]$
$y_{H_2O,\ AFMin}$ Moisture volume fraction of the gas stream which is sent to the AFM $[-]$
$y_{H_2O,\ BP}$ Moisture volume fraction of the gas stream which is bypassed the raw meal department $[-]$
$y_{H_2O,\ G,\ AFMout}$ Moisture volume fraction of the gas stream coming out from AFM, coarse separator, and the cyclone system $[-]$
$y_{H_2O,\ G,\ F,\ in}$ Moisture volume fraction of the mixed gas stream which is sent to the ESP and BF (bypass gas stream + gas stream coming from the raw meal department) $[-]$
$y_{H_2O,\ G,\ in}$ Moisture volume fraction of the gas stream coming from the preheater tower $[-]$
$y_{H_2O,\ G,\ out}$ Moisture volume fraction of the gas stream which is coming out from the ESP and BF and released to the atmosphere $[-]$
$y_{O_2,\ A,\ in}$ Atmospheric oxygen volume fraction $[-]$
$y_{O_2,\ AFMin}$ Oxygen volume fraction of the gas stream which is sent to the AFM $[-]$
$y_{O_2,\ BP}$ Oxygen volume fraction of the gas stream which is bypassed the raw meal department` $[-]$
$y_{O_2,\ G,\ AFMout}$ Oxygen volume fraction of the gas stream coming out from AFM, coarse separator, and the cyclone system $[-]$
$y_{O_2,\ G,\ F,\ in}$ Oxygen volume fraction of the mixed gas stream which is sent to the ESP and BF (bypass gas stream + gas stream coming from the raw meal department) $[-]$
$y_{O_2,\ G,\ in}$ Oxygen volume fraction of the gas stream coming from the preheater tower $[-]$
$y_{O_2,\ G,\ out}$ Oxygen volume fraction of the mixed gas stream which is coming out from the ESP and BF and released to the atmosphere $[-]$

Greek Letters

η_{BF} Bag filter efficiency $[-]$
η_{CS} Coarse separator efficiency $[-]$
$\eta_{Cyclone}$ Cyclone tower/system efficiency $[-]$
η_{ESP} Electro-static precipitator efficiency $[-]$
ρ_{H_2O} Density of the moisture in gas (At normal conditions) $\left[\frac{kg}{Nm^3}\right]$
ρ_A Density of the atmospheric air (At normal conditions) $\left[\frac{kg}{Nm^3}\right]$
ρ_G Density of the gas (At normal conditions) $\left[\frac{kg}{Nm^3}\right]$
ρ_{RM} Density of Limestone $\left[\frac{kg}{m^3}\right]$

Physical constants

C_{p,H_2O} - Specific heat capacity of water $4185 \times 10^{-6} \left[\frac{MJ}{kg \cdot K}\right]$

M_{wH_2O}- Molecular weight of water 0.018 $\left[\frac{kg}{mol}\right]$
P_N - Normal gas pressure 101325 $[Pa]$
T_N - Normal temperature 273.15 $[K]$
R - Universal gas constant 8.314 $\left[\frac{J}{mol\cdot K}\right]$

1. Introduction

The cement industry is a major consumer of energy, in particular thermal energy. As not all the thermal energy can be fully utilized, most plants generate considerable amounts of waste heat in the form of relatively hot exhaust gases coming from the rotary cement kiln system.

Even if part of the thermal energy in the rotary kiln and calciner exit gas (having a temperature of 850–900 °C) is used in a cyclone preheater tower for preheating the kiln feed, there is still a significant amount of waste heat left as the exit gas from the preheater tower typically has a temperature of 300–400 °C.

Most cement plants use part of this hot gas coming from the preheater towers to dry raw materials in the raw meal processing department [1], leaving an exit gas stream temperature of typically 100 °C being released to the surroundings. However, since only part of the hot gas is utilized in this way, there may be significant amounts of energy still available for waste heat utilization. The amount of available heat depends on the moisture content of the raw materials and temperature changes following variations in kiln operation [2].

Most of the available literature on cement kiln waste heat utilization [1,3,4] study the recoverability of the waste heat from the preheater exhaust gas for power generation purposes. In such cases, the cooling towers usually applied in the preheater exit gas to reduce the gas temperature, will be replaced by waste heat boilers, which are part of a power generation system, which could for example be implemented in the form of an Organic Rankine Cycle [5].

The aim of this study is to show that the waste heat not already used for drying raw materials, may be utilized, and this is exemplified by determining the waste heat availability in the raw meal department of a Norwegian cement plant producing approximately 1.3 Mt of cement per year.

2. Process description

The gas stream coming from the kiln is going through the preheater tower (a series of cyclones) to heat up the raw meal (see Fig. 2-1). The hot preheater exit gas, which typically has a temperature of 400 °C, is cooled in a conditioning tower, in which injected water evaporates by means of heat from the gas (direct cooling). The outlet temperature setpoint (controlled by the water injection)

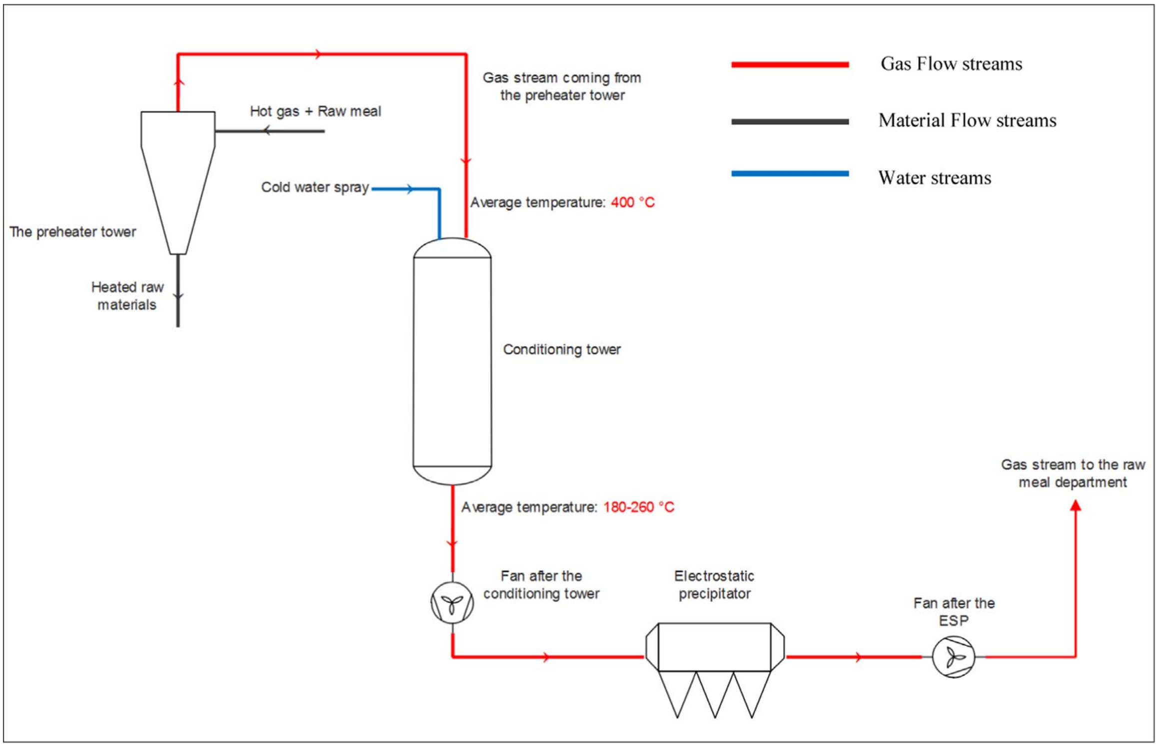

Fig. 2-1. Inlet gas stream path upstream of the raw meal department.

varies from 180 to 260 °C, depending on what gas temperature is required in the raw meal department. The gas flows through an Electrostatic precipitator (ESP) for de-dusting before entering the raw meal department. There are two fans in the system, one downstream of the conditioning tower and another one downstream of the ESP. These are required to overcome the pressure drop in the system.

The gas then enters the raw meal department, see Fig. 2-2. Three types of limestone, with a variable content of calcium carbonate ($CaCO_3$), and different additives (rich in silicon oxide, aluminium oxide and iron oxide) are used in the production of different raw meal types. The mixture of limestones and additives are jointly referred to as "raw material" in Fig. 2-2.

The temperature of the gas coming into the raw meal department via the hot gas fan depends on the type of raw material being processed. Typically, the hot gas temperature at the inlet to the raw meal department is 180 °C for the STD ("standard") type and 260 °C for the HS ("high strength") type. The gas flow rate is around 300 kN m^3/h during normal operation. The gas stream contains O^2, N^2, H^2O and CO^2 as well as some minor components such as SO_x and NO_x. There is also a significant amount of dust (approximately 3 g/Nm^3) coming along with the gas.

The hot gas is separated into two streams, one stream used in the raw meal production process, and a bypass stream. The part of the gas which is sent via the raw meal processing unit first goes through the Aerofall mill (AFM), where the raw materials are grinded and dried. The hot gas coming into the AFM has two purposes, to provide heat for drying of raw materials and to bring the grinded raw materials pneumatically out of the AFM and onwards to the coarse separator and the cyclones [6]. Due to the raw material drying, the amount of moisture in the gas increases. Moreover, a significant amount of false air is sucked into the AFM via the raw material feeding point, increasing the gas flow rate.

The gas stream carrying the grinded and dried raw materials from the AFM is then sent via the coarse separator, which acts as a gravity settler. The gas stream, which now mainly contains fine particles, is then sent through two parallel cyclones for fines separation. The coarse and fine particles are sent to different parts of the raw meal department for further processing (not shown here, as the focus is on the gas phase). A fan and a gas flow control valve (placed after the cyclones) are used to adjust the flow rate of the hot gas required in the AFM. The de-dusted gas next joins with the bypass gas stream.

Although the mixed gas has been de-dusted, it still contains a significant amount of dust, and this dust is largely removed in another ESP and a bag filter (BF) before the gas is released to the surroundings downstream of the filter fan. Some false air is sucked into the ESP and the BF, increasing the gas flow rate further.

The potential for waste heat utilization lies in the bypass gas stream, i.e. the part of the hot gas not required for drying or entrainment of raw materials. This potential waste heat utilization is indicated in Fig. 2-2 with dashed lines. Due to the different grindability and different moisture content of the different raw materials, the gas flow rate in the bypass gas duct varies depending on what type of raw meal is produced (the two main types being STD and HS), meaning that the heat availability also depends on the raw meal type being produced. When AFM is not running, all the gas is sent via the bypass line.

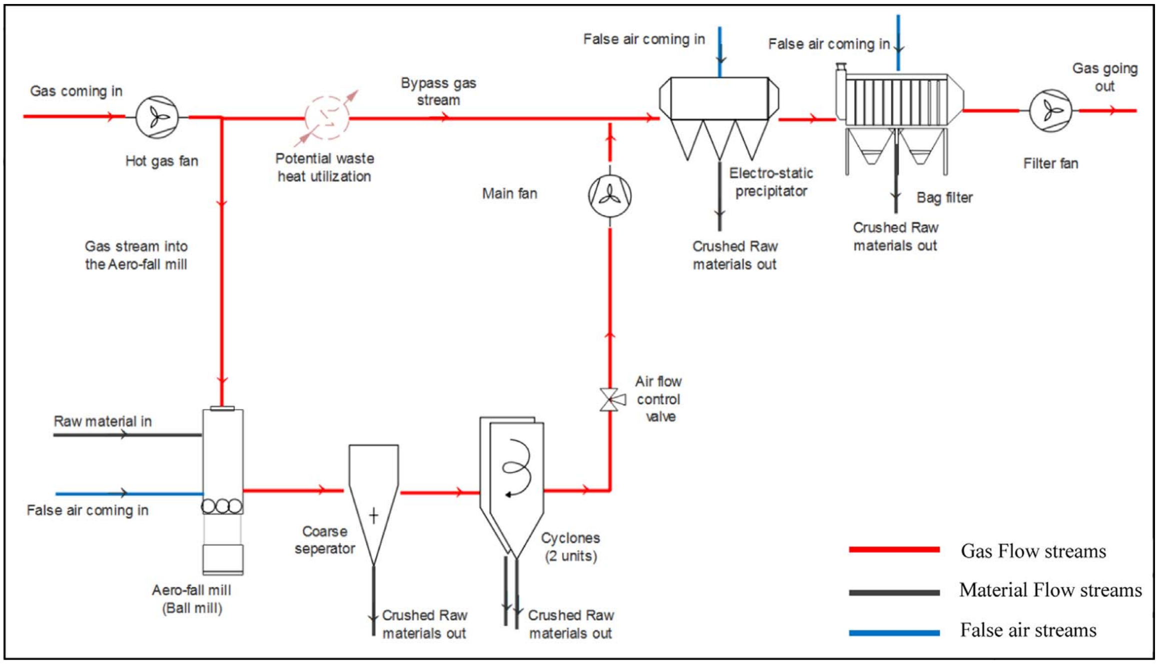

Fig. 2-2. Process flow diagram and the control volume.

3. Method and model development

In order to quantify the available heat in the bypass gas duct at different operating conditions, a model of the raw meal production system (see Fig. 2-2) was established based on a mass and energy balance.

Process data values available from the plant process database were collected, parameters available from the literature as boundary conditions were identified, and required manual measurements of gas flow rates were carried out using a pitot tube to determine the velocities in the gas ducts. To estimate heat losses from the gas ducts and equipment units in the system, the surface temperatures were measured using a laser thermometer.

Appendix A gives the model assumptions and a detailed model description. A block diagram including all symbols applied in the model is given in Fig. 3-1.

4. Results and discussion

4.1. Waste heat availability

Table 4-1, Fig. 4-1 and Fig. 4-2 show the main results related to heat availability in the bypass line for HS production, STD production and no raw meal production (N/R). Furthermore, Table 4-1 shows the process conditions for the different cases.

The flow rates in Table 4-1 are based on manual measurements of selected operational periods, so may not be entirely representative of long-term averages. The higher total flow N/R flow rate (48 Nm^3/h) is most likely a consequence of production rate variations that are due to other factors, for example variations in the burnability of the raw meal. But the basic idea stays the same; all the gas goes via the bypass line when AFM is not running, so then the bypass line has a much larger amount of waste heat available.

There is a high heat availability for production of LP steam when HS is produced and when the AFM is not running (4.2 MW and 4.0 MW respectively). However, even more heat is available (5.8 MW) for generation of hot water. The heat available to generate hot water is approximately the same when HS and STD are produced (2.5 MW and 2.2 MW respectively).

When it comes to the production of LP steam and hot water in the bypass line, STD has the lowest LP steam production rate (0.5 kg/s) because the inlet gas temperature is lower (around 180 °C). The production of hot water rate is very high (67.7 kg/s) when AFM is not running since there is a higher mass flow rate of the bypass gas at a gas temperature around 180 °C.

Fig. 4-3, Fig. 4-4 and Fig. 4–5 show heat streams through the system in the form of Sankey diagrams for HS, STD and no AFM operation, respectively. For each operation case, the heat recovery is shown. Heat flow rates for gas streams, raw material streams, power inputs from fans and from the AFM drive as well as the estimated heat losses are shown in the Sankey diagrams. In all cases, 0 °C has been used as the reference temperature. Furthermore, all Sankey diagrams apply the same scale to facilitate comparison.

The limestone used during STD production is harder to grind than the limestone used during HS production. This means that more gas is required to entrain the particles in the AFM and transfer them to a roller press (not shown in the process flow diagram) for further grinding. However, as the gas flow rate through the AFM increases, the temperature can be reduced and still the same amount of sensible heat for drying can be provided. Oppositely, when HS is produced, the particles are more easily crushed, and less gas is required for entrainment. But to provide the same sensible heat for drying, the temperature of the gas must be higher. This phenomenon is the reason for operating with a higher inlet gas temperature during HS production (around 260 °C) than during STD production (around 180 °C). And this also explains why the waste heat availability is higher during HS production. Accordingly, a lower valve opening is used when HS is produced, as seen in Table 4-1.

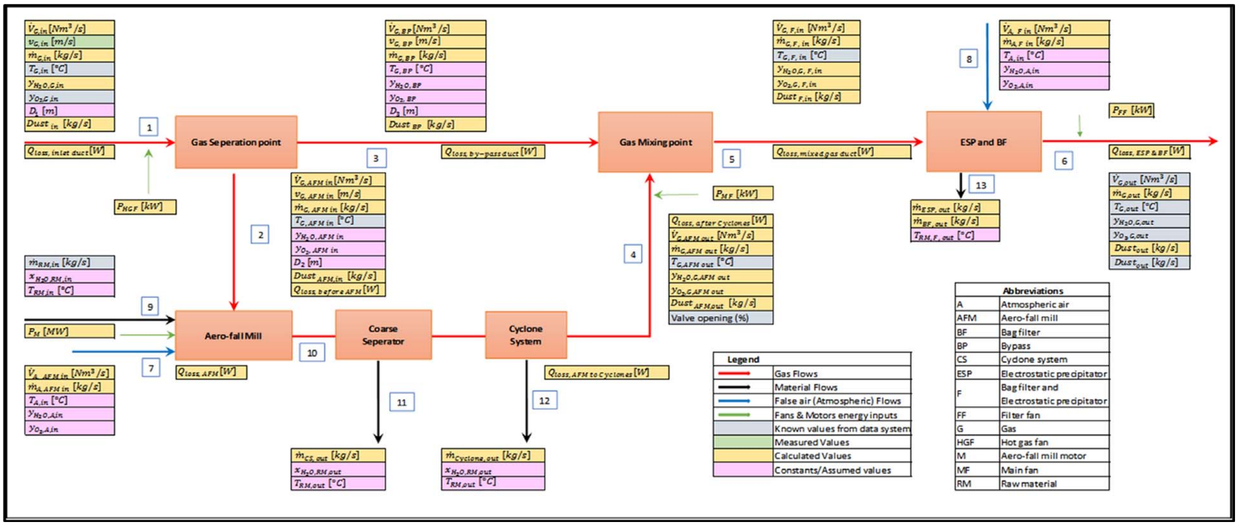

Fig. 3-1. Block diagram of the model.

Table 4-1
Summary of the waste heat availability calculations.

Description	HS	STD	Not running (N/R)	Units
Valve opening	36	66	0	%
Gas flow rate into the AFM ($\dot{V}_{G,\ AFMin}$)	18	23	0	$\frac{Nm^3}{s}$
Bypass gas flow rate ($\dot{V}_{G,\ BP}$)	20	18	48	$\frac{Nm^3}{s}$
Bypass gas temperature ($T_{G,\ BP}$)	266	185	185	°C
Heat availability (ref 0 °C) (Q)	8.2	5.0	13.4	MW

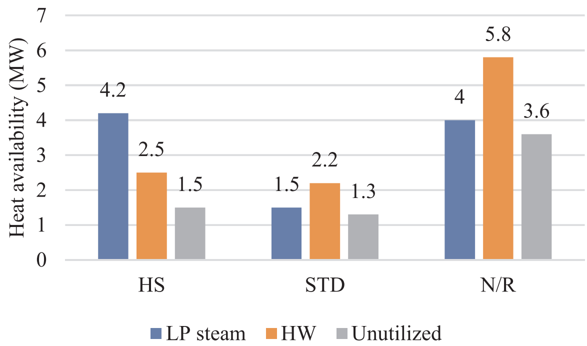

Fig. 4-1. Waste heat availability for different process conditions.

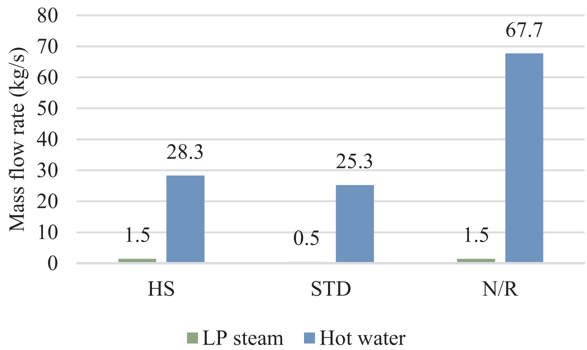

Fig. 4-2. Possible LP steam generation and Hot water generation from the available heat.

4.2. False air in the raw meal department

The amount of false air in the raw meal department is significant according to the model results. It has been estimated that more than 40% of the gas stream leaving the raw meal department is false air (see Table 4-2) when the AFM is in operation. As per the results in Table 4-2, most of the false air is coming into the system via the raw material feeding inlet at the AFM. However, 8–15% of the false air enters the system via the ESP and the BF.

The amount of false air coming into the system via the AFM is important when it comes to the heat recovery at the bypass gas stream. The false air temperature is low (typically between 0 and 25 °C), which means that some of the sensible heat in the hot gas is heat up the false air, reducing the drying potential of the gas. Since one of the main purpose of sending hot gas via the AFM is to dry the raw materials, more air could have been bypassed if the false air was reduced. This means that more heat could have been made available in the bypass gas stream. In other hand when the false air is reduced, then the gas flow rate inside the AFM drops, and then the particle entrainment goes down. Thus, in a way false air is actually required during STD operation in order to maintain the drying capacity and the need for particle entrainment. So, the effect relating to the available heat in the bypass gas stream with the false air coming to the system require further investigation.

4.3. Heat recovery possibility at the conditioning tower when AFM is not running

To maximize the heat availability when the AFM is not running, the temperature of the gas stream could be maximized to 400 °C by cutting the water injection in the conditioning tower. However, this temperature is not optimal for operation of the ESP (see Fig. 2-1 for the ESP location), as the high temperature can possibly damage the ESP parts in the long run. Furthermore, the fan placed

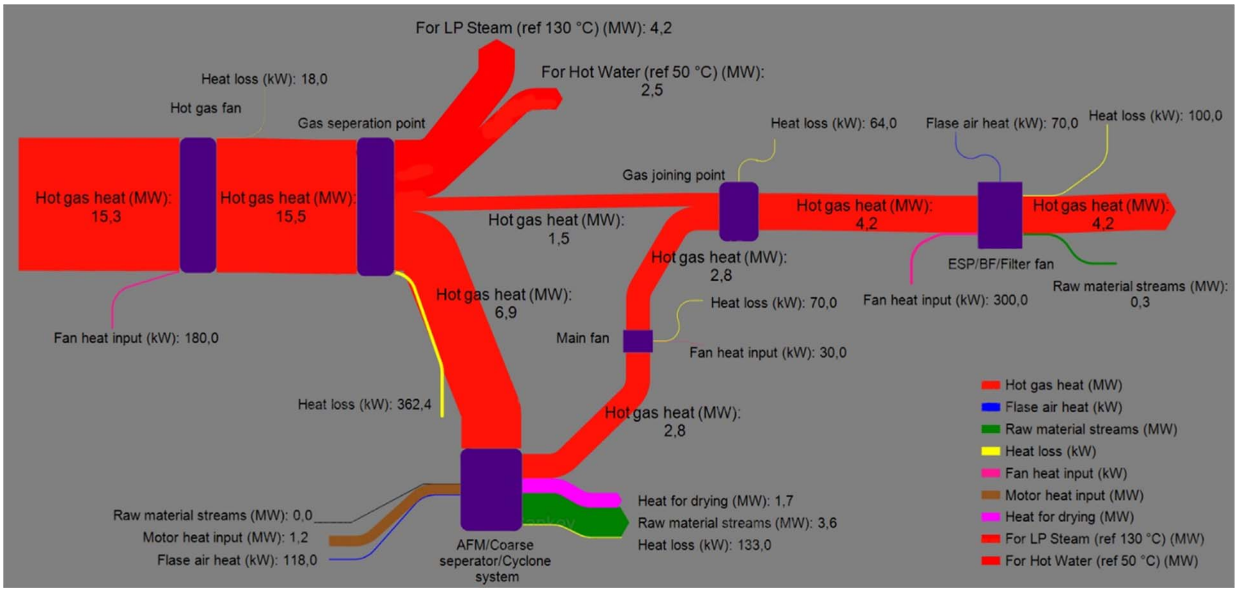

Fig. 4-3. Sankey diagram for the heat flows with possible heat recovery when Type HS is running.

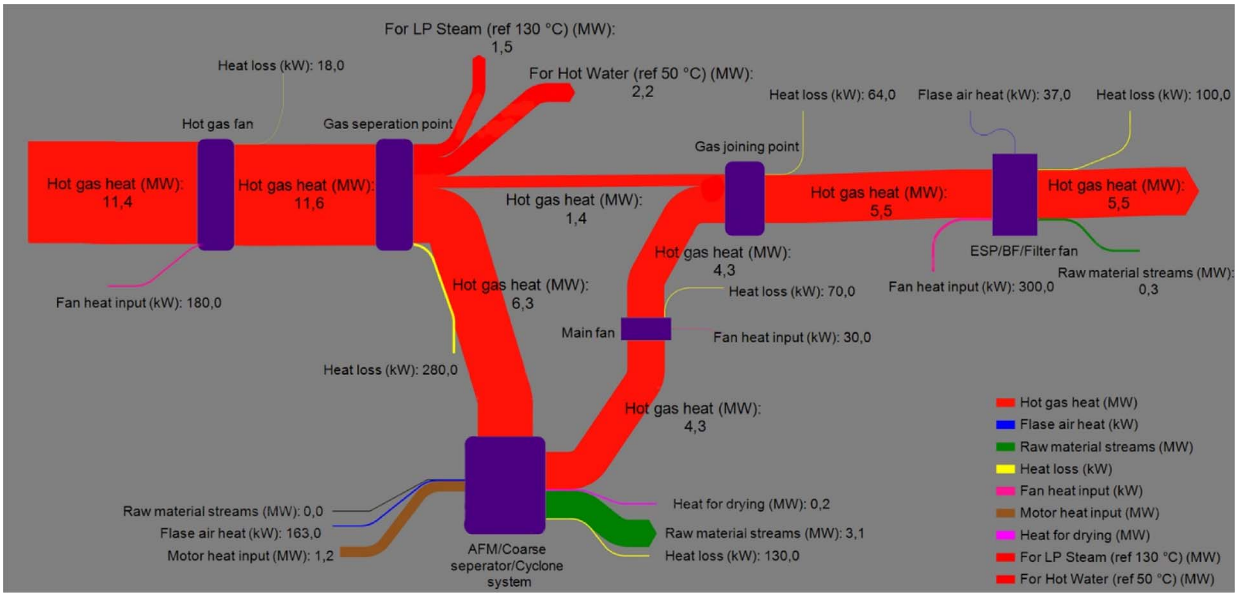

Fig. 4-4. Sankey diagram for the heat flows with possible heat recovery when STD type is running.

downstream of the conditioning tower will not have enough capacity to transport the same amount of gas when the temperature is increased to 400 °C (the absolute gas flow rate is more or less the same, but the mass flow rate goes down due to the density reduction). Actually, this is the main reason why water is added to the hot gas stream. So, when the AFM is not running, an option to recover heat could be to place a heat exchanger upstream of the ESP, in parallel with the conditioning tower, and route the gas through the heat exchanger instead of through the conditioning tower. The specifications used for the calculations and the results are shown in Table 4-3. Averaged data were used as inputs to the calculation. The average yearly available heat is calculated as 52 TJ per year for LP steam generation and 16 TJ per year for hot water generation. On the other hand, such a scheme would have to be evaluated in terms of investments required for additional equipment installation, in particular considering that the annual downtime (N/R) is relatively low, hence the annual run time for the added heat exchanger would be correspondingly low.

4.4. Heat loss from the system

As shown in Table 4-4, the total estimated heat loss is less than 400 kW during HS production. 100 kW heat loss was assumed for

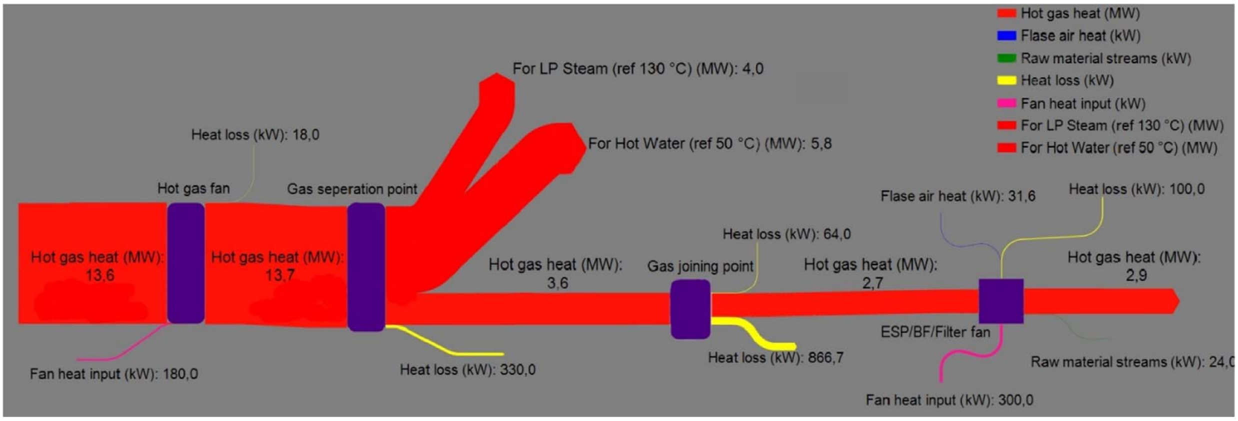

Fig. 4–5. Sankey diagram for the heat flows with possible heat recovery when AFM is not running.

Table 4-2
False air coming into the raw meal department.

Operation	False air at AFM (vol%)	False air at ESP and BF (vol%)	Total false air (vol%)
HS	28%	15%	43%
STD	36%	8%	44%
N/R	0%	9%	9%

Table 4-3
Specifications and results for heat availability calculation at the conditioning tower when AFM is not running.

Description	Value
Average mass flow rate of hot gas via the conditioning tower when AFM is not running	65 kg/s
Average gas temperature before the conditioning tower	400 °C
Assumed downtime of the AFM per week	15 h/week
No of kiln running week	48 weeks/yr
Yearly available LP steam at conditioning tower when AFM not running	52 TJ/yr
Yearly available Hot water at conditioning tower when AFM not running	16 TJ/yr

the ESP and the BF since it was hard to take temperature readings on the surfaces at these locations. The average external heat transfer coefficient was assumed to be 10 W/(m^{2}K), which is a quite typical heat transfer coefficient for free gas convection [7]. As the surface temperatures in the current system are low, radiation heat loss does not contribute very much and was neglected. Assuming an emissivity of 0.5, the estimated heat loss would have increased by approximately 24% if radiation heat loss was also included. Even if uncertainties related to equipment sizes are considered, the total heat loss from the system is low compared to the available heat in the bypass gas stream. The ratio of heat loss to heat availability is around 6% for HS production, and somewhat higher for STD.

Table 4-4
Heat loss estimated for gas ducts and process equipment units during Type HS.

Location	Surface area (A_{sur}) (m^2)	Average temperature (T_{sur}) (°C)	Average heat loss (Q_{loss}) (kW)
At inlet pipe (stream 1)	68	31	18
Towards AFM (stream 2)	20	30	5
Bypass line (stream 3)	79	34	23
Before AFM	32	89	27
At AFM	126	29	30
At two cyclones	265	40	94
Inlet and outlet pipes of cyclones	36	31	9
Before gas mixing, from AFM	14	53	7
To outside line (after gas mixing and before ESP)	68	99	64
At ESP and BF	–	–	100 (assumed)
Total estimated heat loss (kW)			377

4.5. Suggested heat recovery system

For heat recovery, the suggested way is to use a series of heat exchangers to generate LP steam and hot water. Fig. 4–6 shows a suggested heat exchanger system to generate LP steam and hot water using the available heat near the bypass gas stream at the raw meal department. A similar arrangement can be used at the conditioning tower if heat recovery is to be applied at that location when AFM is not running.

Generation of LP steam is suggested until the hot gas temperature has reached 130 °C, whereas hot water generation is suggested for the hot gas temperature interval from 130 to 50 °C.

Saturated LP steam at 120 °C and approx. 200 kPa pressure is produced, and this can be seen as a typical value for industrial LP steam. The medium entering the LP heat exchanger would then be saturated water at 120 °C, returning from the external heat exchange cycle.

Hot water at 60 °C is produced, and this can be seen as a typical hot water temperature required for heating purposes and domestic hot water usage [8]. A return temperature of 40 °C has then been assumed for the water, which will be heated in a counter flow heat exchanger. The output temperatures of the LP steam and the hot water are decided based minimum 10 °C temperature difference to maintain the driving force in the heat exchangers ($\Delta T_{min} > 10 \quad °C$).

4.6. Uncertainties with the calculations

The moisture content of the air and the raw materials can vary in a wide range due to the daily weather conditions. The reason for the variable moisture content in the raw materials is that they are exposed to the environment during excavating, transportation, and outside storage. If the raw material moisture content is higher than the values used into the calculation, more hot gas is required in the AFM to fulfill the drying purpose. Then the actual heat availability in the bypass line will be lower than the estimated value.

The energy inputs from the fan drives and from the AFM drive directly affect the gas stream. A fraction of this energy is lost to the surroundings, and not transferred to the gas as sensible heat. Energy loss due to the noise emissions may also be significant. These losses have not been considered in the calculation, meaning that the available heat may be slightly overestimated.

Under or overestimation of heat losses is also an uncertainty in the calculation.

4.7. Possible issues with heat recovery

Since the gas contains dust and moisture, there is a risk that dust may accumulate inside the heat exchanger and possibly lead to partial gas blockages and reduced heat transfer due to fouling. In many cases, shell-and-tube heat exchangers are used to recover heat from gas streams. If this type of heat exchanger is used, the gas streams should be sent via the tubes to minimize the deposition of dust inside the heat exchanger. If gas stream is sent via the shell side, there is a higher risk of dust deposits due to baffles and other obstacles. Even if the gas is sent via the tubes, dust may accumulate, but most likely at a slower rate, and also with a possibility of activating tube cleaning measures, i.e. proper maintenance procedures need to be followed to remove the accumulated dust inside the tubes.

5. Conclusion

The available heat varies from 1.5 to 4.2 MW for LP steam (0.5–1.5 kg/s) and from 2.2 to 2.5 MW for hot water generation (28–25 kg/s) in the bypass line for STD and HS production, respectively. This means that a significant amount of waste heat is available and can be utilized for energy utilizing purposes.

Approximately 20 MW of LP steam and 6 MW of hot water is available at the conditioning tower before the raw meal department

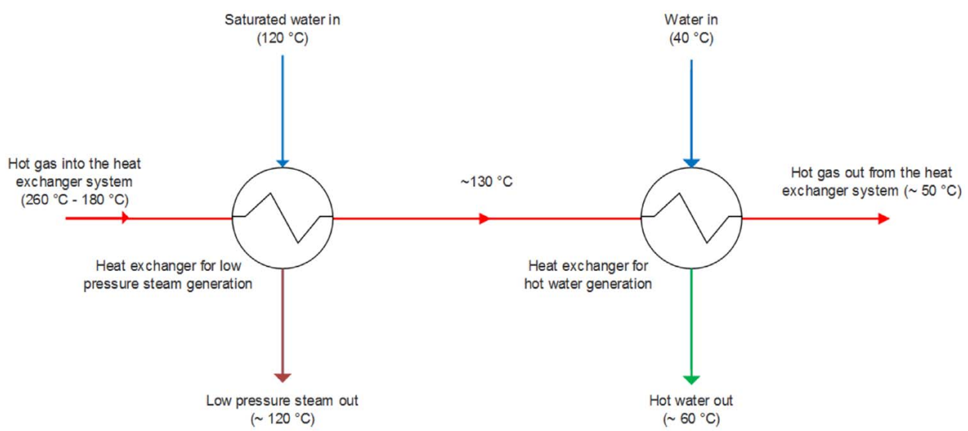

Fig. 4–6. Suggested heat exchanger system for LP steam generation and hot water generation.

when AFM is not running. The average yearly available heat is approximately 50 TJ, taking into account the number of hours per year without AFM in operation.

Based on the calculated heat availability values, it is recommended to extract available heat via the bypass line during HS and STD production and extract heat by bypassing the gas stream from the conditioning tower, leading it through a heat exchanger, when the AFM is not running.

A network of heat exchangers is suggested to recover heat by utilizing it to generate low-pressure stream (~120 °C) and hot water (~60 °C). The heat loss from the system and power inputs from fans and motors are low compared to the available heat.

The total false air coming into the system at different locations has been estimated to 40–50% of the exit gas from the raw meal department.

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Appendix A. Model development

A.a. Assumptions

The following assumptions were made for the model development:

i. The moisture content in false air is assumed to be constant and equal to the moisture content in ambient air, 0.6 vol%.
ii. The raw material moisture content is assumed to be constant and equal to 1 wt% for HS and 0.1 wt% for STD.
iii. All gas streams are treated as incompressible and ideal gases.
iv. Steady state conditions are assumed (temperatures do not vary significantly with time in the considered locations).
v. Gas molecular weight variations in the system are neglected.
vi. The moisture content in the produced raw meal is negligible ($x_{H_2O,\ RM,\ out} = 0$).
vii. The temperatures of the crushed raw materials and the gas exiting from the coarse separator and the cyclone system are equal ($T_{RM,\ out} = T_{G,\ AFMout}$).
viii. The temperature of the bypass gas stream ($T_{G,\ BP}$) is equal to the temperature of the inlet gas stream ($T_{G,\ in}$).
ix. The composition of the bypass gas and the gas stream going into the AFM are both equal to the composition of the inlet gas stream ($y_{O_2,\ G,\ in} = y_{O_2,\ BP} = y_{O_2,\ AFMin}$ and $y_{H_2O,\ G,\ in} = y_{H_2O,\ BP} = y_{H_2O,\ AFMin}$).
x. The energy input from the AFM drive and the fan drives are directly transferred to the gas stream as increased sensible heat.

A.b. Total mass balance

Note: $\dot{m}_{G,\ in}, \dot{m}_{G,\ BP}, \dot{m}_{G,\ AFMin}, \dot{m}_{G,\ AFMout}, \dot{m}_{G,\ F,\ in}, \dot{m}_{G,\ out}$ gas mass flow rates are defined including the dust suspended in the gas streams.

A mass balance for the gas streams around the gas separation point is given by Eq. (A.1), and a mass balance for suspended dust are given in Eqs. (A.2)–(A.4).

$$\dot{m}_{G,\ in} = \dot{m}_{G,\ BP} + \dot{m}_{G,\ AFMin} \tag{A.1}$$

$$Dust_{in} = \frac{\dot{V}_{G,\ in}{}^{*}C_{Dust,\ in}}{1000} \tag{A.2}$$

$$Dust_{BP} = Dust_{in}{}^{*}\frac{\dot{m}_{G,\ BP}}{\dot{m}_{G,\ in}} \tag{A.3}$$

$$Dust_{AFM,\ in} = Dust_{in} - Dust_{BP} \tag{A.4}$$

The mass balance for the gas streams around the AFM, coarse separator and the cyclone system is given by Eq. (A.5), and the mass balance for the solid streams are given by Eqs. (A.6)–(A.8).

$$\dot{m}_{G,\ AFMout} = \dot{m}_{G,\ AFMin} + \dot{m}_{A,\ AFMin} + \dot{m}_{RM,\ in}{}^{*}x_{H_2O,\ RM,\ in} + Dust_{AFM,\ out} \tag{A.5}$$

$$\dot{m}_{CS,\ out} = [\dot{m}_{RM,\ in}{}^{*}(1-x_{H_2O,\ RM,\ in}) + Dust_{AFM,\ in}]^{*}\eta_{CS} \tag{A.6}$$

$$\dot{m}_{Cyclone,\ out} = [\dot{m}_{RM,\ in}{}^{*}(1-x_{H_2O,\ RM,\ in}) + Dust_{AFM,\ in} - \dot{m}_{CS,\ out}]^{*}\eta_{Cyclone} \tag{A.7}$$

$$Dust_{AFM,\ out} = [\dot{m}_{RM,\ in}{}^{*}(1-x_{H_2O,\ RM,\ in}) + Dust_{AFM,\ in} - \dot{m}_{CS,\ out} - \dot{m}_{Cyclone,\ out}] \tag{A.8}$$

The mass balance for the gas streams around the gas mixing point is shown in Eq. (A.9), and the mass balance for suspended dust is given in Eq. (A.10).

$$\dot{m}_{G,\ F,\ in} = \dot{m}_{G,\ BP} + \dot{m}_{G,\ AFMout} \tag{A.9}$$

$$Dust_{F,\ in} = Dust_{BP} + Dust_{AFM,\ out} \tag{A.10}$$

The mass balance for the gas and solid streams around the ESP and the BF is shown in Eqs. (A.11)–(A.14).

$$\dot{m}_{G,\ out} + \dot{m}_{ESP,\ out} + \dot{m}_{BF,\ out} = \dot{m}_{G,\ F,\ in} + \dot{m}_{A,\ Fin} \tag{A.11}$$

$$\dot{m}_{ESP,\ out} = Dust_{F,\ in}{}^{*}\eta_{ESP} \tag{A.12}$$

$$\dot{m}_{BF,\ out} = (Dust_{F,\ in} - \dot{m}_{ESP,\ out})^{*}\eta_{BF} \tag{A.13}$$

$$Dust_{out} = (Dust_{F,\ in} - \dot{m}_{ESP,\ out} - \dot{m}_{BF,\ out}) \tag{A.14}$$

A.c. Component balance

The oxygen (O_2) balance around the AFM, the coarse separator and the cyclone system is given in Eq. (A.15), the oxygen balance around the gas mixing point is given in Eq. (A.16), and the oxygen balance around the ESP and the BF is given in Eq. (A.17).

$$\dot{V}_{G,\ AFMout}{}^{*}y_{O_2,\ G,\ AFMout} = \dot{V}_{G,\ AFMin}{}^{*}y_{O_2,\ AFMin} + \dot{V}_{A,\ AFMin}{}^{*}\, y_{O_2,\ A,\ in} \tag{A.15}$$

$$\dot{V}_{G,\ F,\ in}{}^{*}y_{O_2,\ G,\ F,\ in} = \dot{V}_{G,\ BP}{}^{*}y_{O_2,\ BP} + \dot{V}_{G,\ AFMout}{}^{*}y_{O_2,\ G,\ AFMout} \tag{A.16}$$

$$\dot{V}_{G,\ out}{}^{*}y_{O_2,\ G,\ out} = \dot{V}_{G,\ F,\ in}{}^{*}y_{O_2,\ G,\ F,\ in} + \dot{V}_{A,\ Fin}{}^{*}y_{O_2,\ A,\ in} \tag{A.17}$$

The moisture (H_2O) balance at the gas mixing point is given in Eq. (A.18), while the moisture balance over the ESP and the BF is given in Eq. (A.19).

$$\dot{V}_{G,\ F,\ in}{}^{*}y_{H_2O,\ G,\ F,\ in} = \dot{V}_{G,\ BP}{}^{*}y_{H_2O,\ BP} + \dot{V}_{G,\ AFMout}{}^{*}y_{H_2O,\ G,\ AFMout} \tag{A.18}$$

$$\dot{V}_{G,\ out}{}^{*}y_{H_2O,\ G,\ out} = \dot{V}_{G,\ F,\ in}{}^{*}y_{H_2O,\ G,\ F,\ in} + \dot{V}_{A,\ Fin}{}^{*}y_{H_2O,\ A,\ in} \tag{A.19}$$

The moisture balance around the gas separation point, the AFM and the gas mixing point (i.e. for stream numbers 1, 5, 7, 9, 11 and 12 shown in Fig. 3-1) is shown in Eq. (A.20).

$$\begin{aligned}\dot{V}_{G,\ in}{}^{*}y_{H_2O,\ G,\ in}{}^{*}\rho_{H_2O} + \dot{m}_{RM,\ in}{}^{*}x_{H_2O,\ RM,\ in} + \dot{V}_{A,\ AFMin}{}^{*}y_{H_2O,\ A,\ in}{}^{*}\rho_{H_2O} = \dot{V}_{G,\ Fin}{}^{*}y_{H_2O,\ G,\ F,\ in}\\ {}^{*}\rho_{H_2O} + (\dot{m}_{CS,\ out} + \dot{m}_{Cyclone,\ out})^{*}x_{H_2O,\ RM,\ out}\end{aligned} \tag{A.20}$$

A.d. Energy balance

The energy balance around the gas separation point is given by the Eq. (A.21), and the energy balance for the gas streams around the gas mixing point is given by Eq. (A.22).

$$\dot{m}_{G,\ in}{}^{*}C_{p,G}{}^{*}T_{G,\ in} + P_{HGF} = \dot{m}_{G,\ BP}{}^{*}C_{p,G}{}^{*}T_{G,\ BP} + \dot{m}_{G,\ AFMin}{}^{*}C_{p,G}{}^{*}T_{G,\ AFMin} + Q_{loss} \tag{A.21}$$

$$\dot{m}_{G,\ F,\ in}{}^{*}C_{p,G}{}^{*}T_{G,\ F,\ in} + \dot{m}_{G,\ BP}{}^{*}C_{p,G}{}^{*}T_{G,\ BP} + P_{MF} + \dot{m}_{G,\ AFMout}{}^{*}C_{p,G}{}^{*}T_{G,\ AFMout} - Q_{loss} \tag{A.22}$$

The energy balance for the streams around the AFM, the coarse separator and the cyclone system is given by the Eq. (A.23).

$$\begin{aligned}\dot{m}_{G,\ AFMin}{}^{*}C_{p,G}{}^{*}(T_{G,\ AFMin} - T_{G,\ AFMout}) + P_M = (\dot{m}_{CS,\ out} + \dot{m}_{Cyclone,\ out})^{*}C_{p,RM}{}^{*}(T_{RM,\ out} - T_{RM,\ in}) + \dot{m}_{A,\ AFMin}{}^{*}C_{p,A}\\ {}^{*}(T_{G,\ AFMout} - T_{A,\ in}) + \dot{m}_{RM,\ in}{}^{*}x_{H_2O,\ RM,\ in}\\ {}^{*}\left[L + C_{p,H_2O}{}^{*}(T_{G,\ AFMout} - T_{RM,\ in})\right] + Q_{loss}\end{aligned} \tag{A.23}$$

The energy balance for the gas streams around the ESP and the BF is given by the Eq. (A.24).

$$\dot{m}_{G,\ F,\ in}{}^{*}C_{p,G}{}^{*}T_{G,\ F,\ in} + \dot{m}_{A,\ Fin}{}^{*}C_{p,A}{}^{*}T_{A,\ in} + P_{FF} = \dot{m}_{G,\ out}{}^{*}C_{p,G}{}^{*}T_{G,\ out} + (\dot{m}_{ESP,\ out} + \dot{m}_{BF,\ out})^{*}C_{p,RM}{}^{*}T_{RM,\ F,\ out} + Q_{loss} \tag{A.24}$$

A.e. Mass flow rates

The normal flow rate conversion from velocities is given in Eqs. (A.25)–(A.27), while the mass flow rate conversion from normal flow rates is given in Eqs. (A.28)–(A.35).

$$\dot{V}_{G,\ \ in} = \frac{\pi}{4}*D_1{}^2*v_{G,\ \ in}*\frac{T_N*P}{T_{G,\ \ in}*P_N} \tag{A.25}$$

$$\dot{V}_{G,\ \ BP} = \frac{\pi}{4}*D_3{}^2*v_{G,\ \ BP}*\frac{T_N*P}{T_{G,\ \ in}*P_N} \tag{A.26}$$

$$\dot{V}_{G,\ \ AFMin} = \frac{\pi}{4}*D_2{}^2*v_{G,\ \ AFMin}*\frac{T_N*P}{T_{G,\ \ in}*P_N} \tag{A.27}$$

$$\dot{m}_{G,\ \ in} = \rho_G*\dot{V}_{G,\ \ in} \tag{A.28}$$

$$\dot{m}_{G,\ \ BP} + \rho_G*\dot{V}_{G,\ \ BP} \tag{A.29}$$

$$\dot{m}_{G,\ \ AFMin} = \rho_G*\dot{V}_{G,\ \ AFMin} \tag{A.30}$$

$$\dot{m}_{A,\ \ AFMin} = \rho_A*\dot{V}_{A,\ \ AFMin} \tag{A.31}$$

$$\dot{m}_{G,\ \ AFMout} = \rho_G*\dot{V}_{G,\ \ AFMout} \tag{A.32}$$

$$\dot{m}_{A,\ \ Fin} = \rho_A*\dot{V}_{A,\ \ Fin} \tag{A.33}$$

$$\dot{m}_{G,\ \ Fin} = \rho_G*\dot{V}_{G,\ \ Fin} \tag{A.34}$$

$$\dot{m}_{G,\ \ out} = \rho_G*\dot{V}_{G,\ \ out} \tag{A.35}$$

A.f. Gas densities

The densities of gas, atmospheric air and moisture (water vapor) at normal conditions are given in Eqs. (A.36)–(A.38).

$$\rho_G = \frac{P_N*M_{wG}}{R*T_N} \tag{A.36}$$

$$\rho_A = \frac{P_N*M_{wA}}{R*T_N} \tag{A.37}$$

$$\rho_{H_2O} = \frac{P_N*M_{wH_2O}}{R*T_N} \tag{A.38}$$

A.g. Available heat

The available heat in the bypass gas stream respect to a reference temperature (here set to 0 °C) is given in Eq. (A.39). Possible LP steam generation heat and hot water generation are given in Eqs. (A.40) and (A.41), respectively.

$$Q = \dot{m}_{G,\ \ BP}*Cp_G*(T_{G,\ \ BP} - T_{ref0}) \tag{A.39}$$

$$Q_{LP} = \dot{m}_{G,\ \ BP}*Cp_G*(T_{G,\ \ BP} - T_{ref1}) \tag{A.40}$$

$$Q_{HW} = \dot{m}_{G,\ \ BP}*Cp_G*(T_{ref1} - T_{ref2}) \tag{A.41}$$

Eqs. (A.42) and (A.43) show the equations that are used to calculate the possible production of LP steam ($\dot{m}_{steam}$) and hot water ($\dot{m}_{H_2O}$) from the available heat.

$$Q_{LP} = \dot{m}_{steam}*h_s \tag{A.42}$$

$$Q_{HW} = \dot{m}_{H_2O}*Cp_{H_2O}*(T_{HW,\ \ out} - T_{HW,\ \ in}) \tag{A.43}$$

A.h. Heat loss

Eqs. (A.44) is used to estimate the heat losses from the gas ducts and process units at different locations (here i denotes a respective location).

$$Q_{loss,\ \ i} = U*A_{sur,\ \ i}*(T_{sur} - T_{A,\ \ in}) \tag{A.44}$$

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