# WASTE HEAT UTILIZATION FROM A SUBMERGED ARC FURNACE PRODUCING FERROSILICON

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## ABSTRACT

*This paper addresses some of the technical aspects related to waste heat recovery from ferrosilicon production in a Submerged Arc Furnace. More than half of the energy supplied to the furnace in the form of electricity and black raw materials is lost to the environment as heat. Possibilities for utilizing waste heat at Elkems plant Grundartangi in Iceland were studied, with emphasis on electricity production. Other utilization possibilities considered are district heating and steam generation. Elkem Iceland currently produces two categories of products, ferrosilicon and microsilica, but there is a potential for the third product by utilizing the waste heat. An energy and exergy analysis on a 47 MW furnace producing FeSi75 is preformed based on measurements and data from Elkem Iceland. The production of ferrosilicon involves large exergy destruction, estimated to be 46.5 MW, and the exergetic efficiency of the furnace is about 30%. The energy analysis shows that much of the energy used in the production of ferrosilicon at Grundartangi goes out to the environment as waste heat. Only 35.6 MW of the 98 MW of the energy supplied to the process are retrieved as chemical energy in the product. Comparison of ORC and steam Rankine cycle configurations were performed, given certain design constraints on the investment, and the best configuration gave maximum net power of about 10 MW and 8 MW, respectively. If the waste heat is used in district heating it could supply about 11800 $m^3$/day of water at 80°C to a nearby municipality.*

## 1 INTRODUCTION

Historically, heat recovery in the ferroalloy industry was initiated by the need to cool the off gas before it enters the filters. According to [1] of 16 ferroalloy plants in Norway, 3 recover heat to electric power by steam Rankine cycle and 5 produce thermal energy.

The Elkem ferrosilicon plan located at Grundartangi in Iceland, has two 36 MW furnaces and one 47 MW furnace. The focus of this study is alternative ways to utilize waste heat from the 47 MW furnace. The main product of Elkem Iceland is ferrosilicon, mostly FeSi75 from this particular furnace, and a byproduct is condensed silica fume (CSF), in the form of amorphous $SiO_2$. Recoverable heat could become a third product but it is not harnessed in the current configuration [2]. An energy and exergy analysis is performed on one of the furnaces at Grundartangi. The utilization of the heat is considered with emphasis on electricity production but district heating is also considered. According to Tveit [3] there is considerable variability in the composition and temperature of waste gas from ferrosilicon furnace. These variations occur during normal furnace operation due to actions such as stoking and charging. The heat in the flue gas can only be extracted until the temperature reaches a lower limit set by the acid dew point in the gas. If the temperature drops below that, acid will condense due to the $SO_2$ content in the gas, and severe corrosion takes place. Another difficulty encountered in heat recovery from this source is fouling due to particle deposition on heat exchange surfaces. The shear forces in the off-gas flow are not able to stop deposition of material on the tubes and therefore external cleaning is needed [4]. In this study the main focus is on the energy flow in the system, and the thermodynamics of heat recovery.

## 2 ENERGY AND EXERGY ANALYSIS

The system studied is furnace no. 3 at Elkem Iceland. The first step of the analysis is developing a model to evaluate all the different chemical, mass and energy relations. From these relations, input data from Elkem Iceland, and on site measurements of flow rates and temperatures the energy and exergy analysis is made.

### 2.1 Chemical Model of the furnace – Energy analysis

To form a basis for the thermodynamic analysis a chemical model of the furnace was developed with a focus on energy and material balance for the system. The assumptions for the model are: 1) Furnace operation is assumed to be at steady state; 2) Air is considered to be composed of 20% $O_2$ and 80% $N_2$; 3) Chemical reactions are considered to run to completion 4) The changes of potential and kinetic energy of materials going into the furnace and coming out of the furnace are neglected; 5) Gases are assumed as ideal. As described in [2] the ferrosilicon process flow can be divided into four main parts: 1) Upper part of the furnace - Heat exchange between the electrode, cold raw material and the furnace gas. 2) Submerged arc furnace - Reduction of iron oxide and quartz takes place; 3) Product treatment - Solidification and cooling of the metal. 4) Gas treatment - the combustion of gas from the furnace by adding air. This segmentation of the furnace is illustrated graphically in Figure 1 with the assumed temperatures of the process streams.

The overall reaction of the model is in the *submerged arc furnace* part and is that the reduction of the quartz and iron oxide with carbon and electricity:

$$a \cdot SiO_2 + b \cdot C + f \cdot FeO = c \cdot Si + d \cdot SiO + e \cdot CO + g \cdot Fe \qquad (1)$$

and the coefficient can be found with mass balance and are based on the silicon yield, R as reported by the smelter . The gas products of the chemical reaction are considered to be at 1400 °C when they emerge from the surface of the furnace burden, and the metal products are at 1600 °C. Above the burden, the gas products mix with excess air and burn, CO to $CO_2$ and SiO to $SiO_2$. Not all of the gases are burned there however as a part of the CO reduces the hematite, $Fe_2O_3$, in the charge to iron oxide, FeO, as presented in:

$$\frac{f}{2} \cdot Fe_2O_3 + \frac{f}{2} \cdot CO = f \cdot FeO + \frac{f}{2} \cdot CO_2 \qquad (2)$$

*Other considerations*

The following modifications to this simplified process model must be implemented: 1) energy losses from the process, 2) the use of non-pure carbon 3) carbon losses to the off-gas system and 4) other minor deviations from an ideal process.

The energy losses show up as heat in the cooling water, heat in the furnace gas and heat from the body of the furnace. Also electric power is dissipated through ohmic heating of the electrode. A part of that heat is consumed by baking the Söderberg electrode, but the rest is transferred as heat to the furnace gas. Data for pure carbon is used in the process model is but in reality carbon materials such as coal, coke, charcoal and wood chips are used. These materials include moisture, volatiles, ash and other elements which must be considered in the stochiometry.

Some of the carbon used in the ferrosilicon process is lost to the furnace gas by draft, where it burns in air. This carbon loss is typically around 5 % but varies from furnace to furnace. Other minor deviations are due to e.g. minor elements, like aluminum oxides, that are recovered in the product and "steal" energy from the process as they are reduced with the ferrosilicon [2].

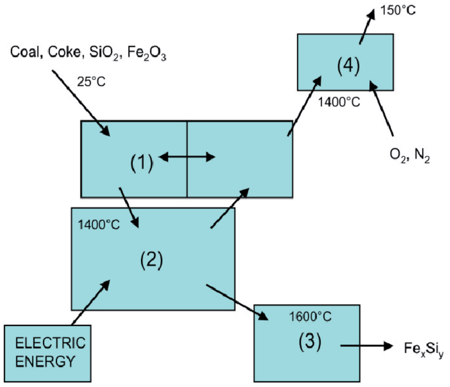


**Figure 1:** The principal process flow in a ferrosilicon production process [15]

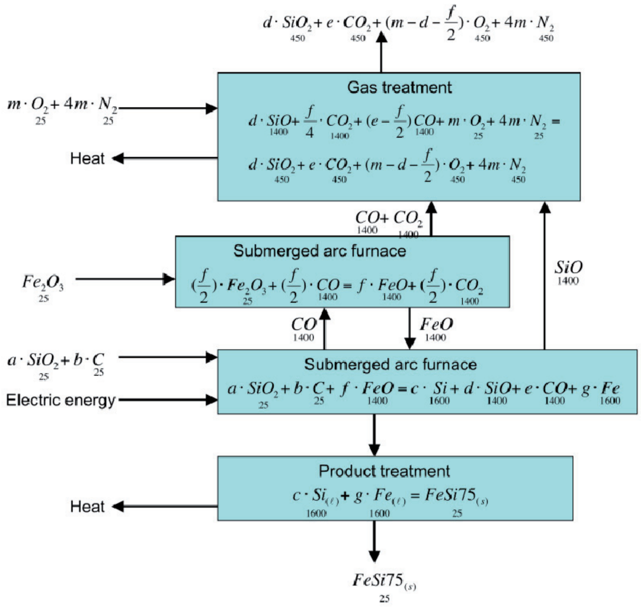


**Figure 2:** Chemical model of the furnace

*Input materials*

The carbon materials fed to furnace 3 in Grundartangi are only Coke and Coal. Chemical analysis of the carbon materials was used to estimate the amount of carbon, volatiles and moisture supplied to the furnace. Other minor elements were ignored. The volatiles in the carbon materials are assumed to be methane, $CH_4$, and burn in the *gas treatment* part of the furnace. They do not take part in the reduction process [2] but add energy to the process. The quartz was also considered to be pure and all the iron to the process was assumed to be hematite. According to input data from Elkem Iceland the energy of input materials and electricity is estimated and presented in Table 1. The mean silicon yield for the time period was R = 89%. The calculated energy use from the theoretical model to reduce the quartz was 34.2 MW while the actual measured power use at Elkem was 39.7 MW. The deviation is 16% which according to [2] corresponds to the mean difference in the theoretical energy usage and the measured energy usage of a real furnace is 16%. The estimated carbon consumption in the process is 8 % less than used in this furnace during the period considered.

**Table 1:** Estimated energy delivered to furnace 3 at Elkem Iceland

| Energy type | Energy into the process | Part |
|---|---|---|
| Electric energy | 39.7 MW | 40 % |
| Chemical energy fix carbon | 33.1 MW | 34 % |
| Chemical energy volatiles | 25.2 MW | 26 % |
| Total | 98 MW | 100% |

*Energy losses*

The main energy losses are: heat in the cooling system, losses directly from the furnace and heat lost by the furnace gas. This is illustrated in a simplified schematic of the furnace in Figure 3, where $\dot{Q}_{OG}$ is heat losses in Off-Gas, $\dot{Q}_{CS}$ is heat loss through the Cooling System, $\dot{Q}_{FB}$ is heat lost from Furnace Bottom and $\dot{Q}_{FS}$ is heat lost from Furnace Sides. The energy losses for furnace 3 have been estimated from measurements and data analysis at Elkem Iceland [5]. The results are summarized in Table 2. The rest of the heat from the chemical reactions in the process is assumed to be transferred to excess air above the burden. Therefore any error in the measurements will turn up as an error in calculated furnace flue gas heat.

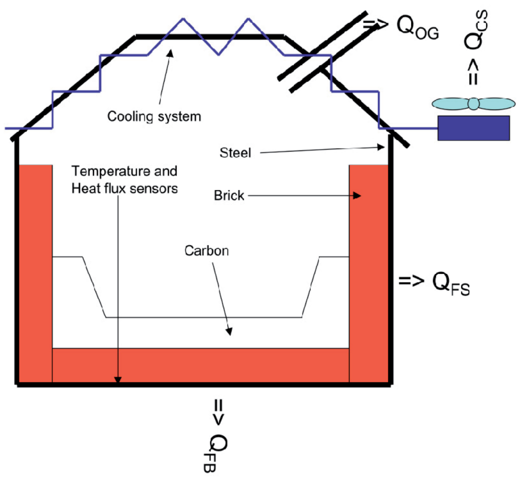


**Figure 3:** Simplified schematic of furnace 3 at Elkem Iceland and energy losses

**Table 2:** Estimated and measured energy streams from furnace 3 in Elkem Iceland

| **Energy type** | **Energy from the process** | **Part of output** |
|---|---|---|
| Chemical energy product | 35.6 MW | 35 % |
| Heat in product | 3.5 MW | 4 % |
| Energy in off-gas ($\dot{Q}_{OG}$) | 45.5 (43.5) MW | 46 % |
| Cooling system, $\dot{Q}_{CS}$ | 12.7 MW | 13 % |
| Directly from furnace body, $\dot{Q}_{FB} + \dot{Q}_{FS}$ | 0.8 MW | 1 % |
| Total | 98 MW | 100 % |

The results show that most of the heat is contained in the furnace gas. The model estimate is 5 % higher than the estimated heat in the off-gas from the measurements. This is small error and the reason for this difference could be that reduction of minor elements is not taken into account and that the heat loss directly from the furnace is underestimated. A Sankey diagram based on the results from the model is presented in Figure 4.

The Sankey diagram shows that of the total 98 MW of energy supplied to the furnace only 35.6 MW is contained as chemical energy in the product. The rest of the energy is waste heat and a good portion of that heat could be recovered by simple means.

## 2.2 Exergy analysis

Exergy is a measure of the quality of energy, its usefulness depending on the environment. Exergy is calculated depending on a reference state, the so-called dead state. A system is said to be in dead state when it is thermodynamic equilibrium with the environment. In this analysis the dead state is defined the same as the standard state, that is: $t_0$ = 25°C and $p_0$ = 100kPa. This choice of a dead state temperature will not give an overestimate of the exergy with the Icelandic climate. In this calculation the potential and kinetic exergy can be ignored. The remaining physical exergy associated with stream of matter is:

$$\dot{E}_{ph} = (h - h_0) - T_0 \cdot (s - s_0) \qquad (3)$$

where *h* and *s* are enthalpy and entropy of the stream and $h_0$,, $s_0$ and $T_0$ are enthalpy, entropy and temperature of the dead state. Chemical exergy can be defined as equal to the minimum work that has to be done to the environment to synthesis the chemicals that are considered, only by using heat transfer and exchanges of substances that are found in the environment.

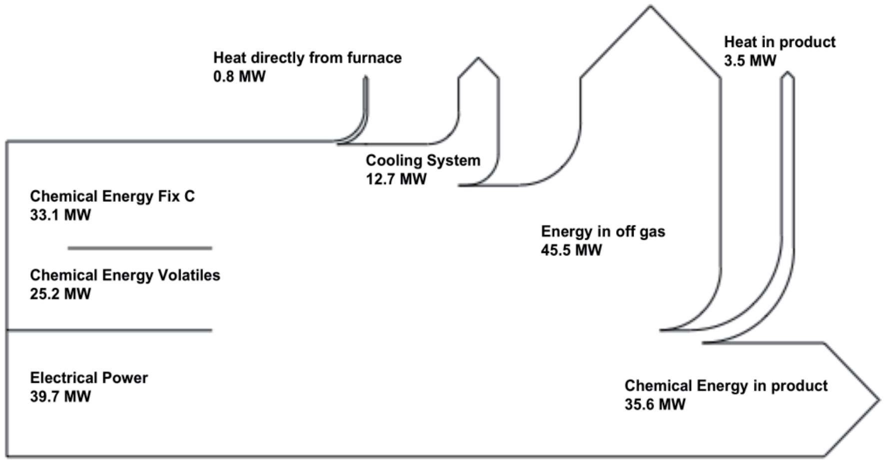


**Figure 4:** A Sankey diagram of furnace 3 at Elkem Iceland Grundartangi based on the calculated results from the model

For solid substances at atmospheric pressure the standard chemical exergy, $\tilde{\varepsilon}^0$ (kJ/kmol) is used [6]. For a gas mixture at atmospheric pressure it is necessary to account for different composition from the environment and the following equation is used:

$$\dot{E}_0 = \sum x_i \cdot \tilde{\varepsilon}^0 + \tilde{R} \cdot T_0 \cdot \sum x_i \cdot \ln(x_i) \qquad (4)$$

where $x_i$ is the molar portion of gas mixture component $i$ and $\tilde{R}$ is the universal gas constant [7].

*The furnace*

For the exergy analysis of the furnace the same assumptions are made in the chemical model as in the energy analysis. The exergy equations were employed on the model and the exergy of the material streams and electricity entering the furnace and material streams exiting were evaluated. The results for the exergy into the furnace are presented in Table 3. The air is considered to have zero exergy as it is part of the environment. The exergy of the streams exiting the furnace are presented in Table 4. It can be clearly seen that the quality of the energy from the cooling system is very low. The exergy is only about 1 MW which is 2 % of the output as compared to 13 MW in and 13 % of the output in the energy analysis.

**Table 3:** Estimated exergy delivered to furnace 3 in Elkem Iceland

| Exergy type | E_ph | E_0 | E_ph+E_0 | Part |
|---|---|---|---|---|
| Electric energy | 39.7 | 0 | 39.7 | 40 % |
| Raw material | 0 | 58.4 | 58.4 | 60 % |
| Air | 0 | 0 | 0 | 0 % |

**Table 4:** Estimated exergy from furnace 3 in Elkem Iceland

| Exergy stream | E_ph | E_0 | E_ph+E_0 | Part |
|---|---|---|---|---|
| Exergy in product | 2.6 MW | 29.5 MW | 32.1 MW | 62 % |
| Exergy in off-gas | 16.9 MW | 1.5 MW | 18.4 MW | 35.5 % |
| Cooling system | 1 MW | 0 | 1 MW | 2 % |
| From furnace body | 0.2 MW | 0 | 0.2 MW | 0.5 % |

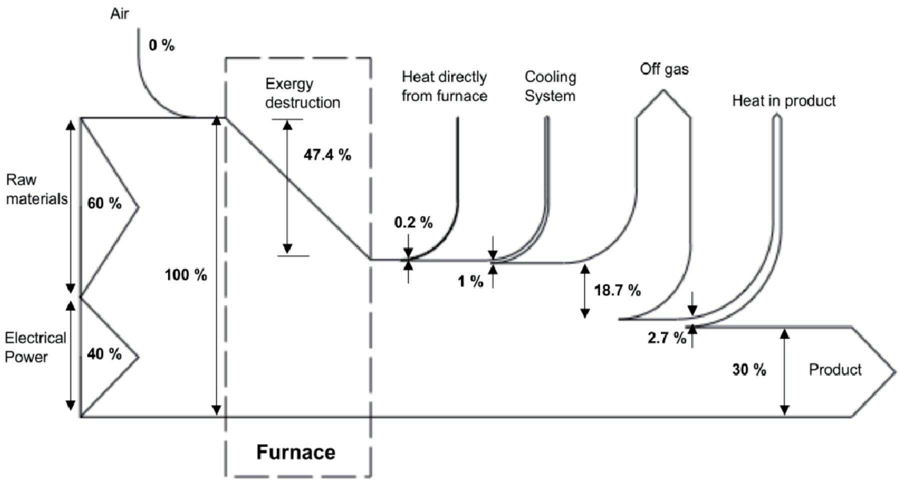


**Figure 5:** A Grassmann diagram of furnace 3 at Elkem Iceland Grundartangi based on the calculated results from the model. The ratios of the streams are based on the input.

The exergy destruction in the furnace is about 46.5 MW and the exergetic efficiency, based on the the metal being the only product, is about 30 %. If energy would be recovered by any means, e.g. electricity production, the exergetic efficiency would increase. In Figure 5 a Grassmann diagram is presented which shows the exergy streams graphically.

If an energy recovery system were to be implemented, a different kind of cooling system should be designed, which would operate at higher temperature, i.e. evaporative cooling a cooling system that allows for hotter water. With evaporator cooling though, more strain is put on the furnace equipment, as it is has to endure higher temperatures, which will shorten the lifetime of the furnace [8].

## 3 ELECTRIC POWER PRODUCTION

The power cycles considered in this study are Rankine Cycle using either water or organic fluids and such a recovery systems are illustrated in Figures 6 and 7. Grundartangis location makes it feasible to utilize the ocean as a heat sink.

### 3.1 Working fluid

Steam is the most commonly used working fluid in power cycles used for waste heat recovery from silicon and ferrosilicon. However organic fluids are more flexible when it comes to heat exchange from the furnace gas. According to [1], it is advised to avoid technologically complicated solutions in the process of heat recovery in ferroalloy industries but the complexity level of the ORC is comparable to the steam Rankine cycle. The downside of using organic fluid in the cycle may however be possible toxicity of the fluid itself.

Waste heat utilization can be divided into three types based on the temperature of the waste heat stream [11]. High temperature is about 500°C and over and often in such cases the water is the best working fluid. Low temperature is defined as below 200 °C and ORC, Kalina and other methods have an advantage over the steam in that range. In the medium range, between 200°C and 500 °C both steam and organic working fluids have their advantage. The advantage of organic fluid is that its specific vaporization heat is much lower than that of water and therefore the temperature in the organic working fluid "follows" better that of the heat source fluid to be cooled, reducing entropy generation [11].

The possible working fluids for use in Rankine cycle are many and the choice comes down to good thermodynamic properties. When an organic working fluid is being considered the following has to be kept in mind: toxicity, explosion- and flammability characteristic, material compatibility and fluid stability limits [10].

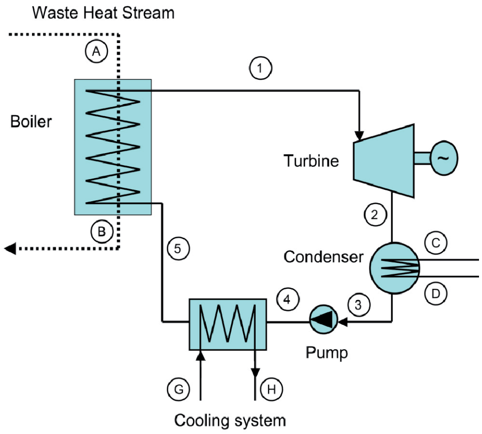


**Figure 6:** A schematic for steam Rankine power cycle for heat recovery at Grundartangi

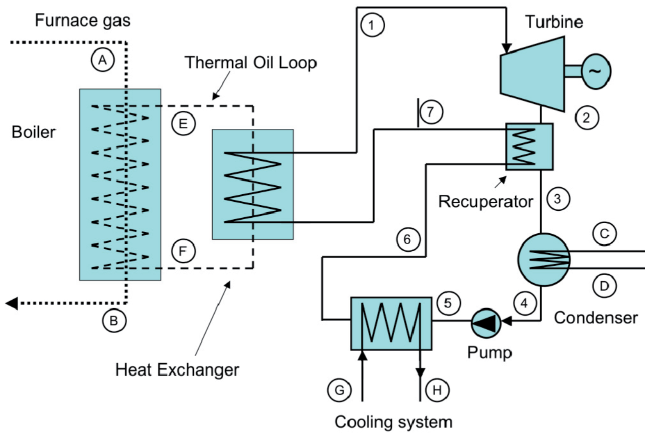


**Figure 7:** A schematic for Organic Rankine power cycle for heat recovery at Grundartangi

*Modeling and optimization*

The modeling software was developed using MATLAB and the thermodynamic data originates from REFPROP [12]. The optimization software used is an evolutionary optimization algorithm developed by Thomas Philip Runarsson and Xin Yao [13]. The modeling does not account for heat- and friction losses in pipes and equipment.

### 3.2 Steam Rankine working cycle

A steam Rankine cycle design proposed for heat recovery at Grundartangi is shown in Figure 6. Modeling details are reported in [5] but one of the important considerations is that the present superstructure cooling system delivers low quality heat. If a power generating heat recovery system were implemented, a superheater could be implemented in the smokehood which would call for a redesign and expensive reconstruction of the furnace smoke hood.

*Optimization and constraints*

No heat- or friction losses are accounted for, efficiency of turbine is assumed to be 85 % and efficiency of pump 50 %. The objective of the optimization is to maximize the power output from the power plant by varying the temperature and pressure of the steam exiting the boiler. The constraints are: 1) Steam quality cannot be lower than 85 %; 2) Pinch in all heat exchangers cannot be less than $\Delta T$ = 5 °C; 3) Furnace gas is fixed at 450°C down to 220°C; 4) Condenser pressure is fixed at 5 kPa and is restricted by the turbine size; 6) The maximum steam pressure is 50 bar.

*Results for steam Rankine cycle*

The TS diagram for the special steam Rankine cycle is in Figure 8 and the temperature profile of the heat exchanges in the for the same cycle are shown in Figure 9.

The maximum net power output is 7.96 MW. The benefit of using the CS for preheating are negligible and the gain in net power production is less than 1 %. The energy used from the Cooling System is only 0.33 MW of the total 13 MW that are available. Therefore most of the energy in the CS is thrown away and the contribution to electricity production is small. The use of the CS also results in a drop both in the thermal efficiency and the second law efficiency. The main reason for this behavior is that the temperature of the heat supplied by the CS is low. Higher efficiency is related to the higher temperatures of the heat source. If the CS would be redesigned and higher temperatures available the effect on the working cycle would be good because then it would serve better as a preheater before the boiler.

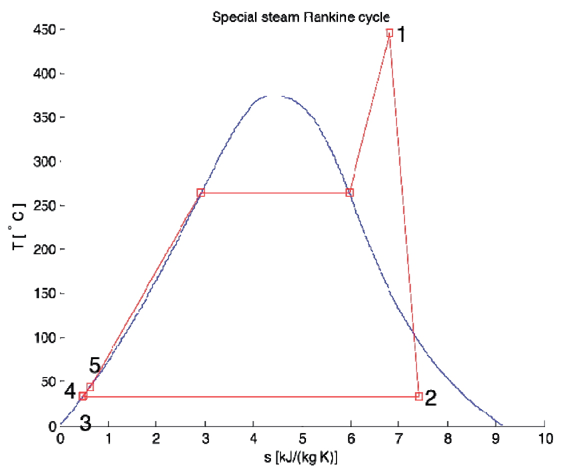


**Figure 8:** A TS diagram of the optimum state for the special Steam Rankine cycle.

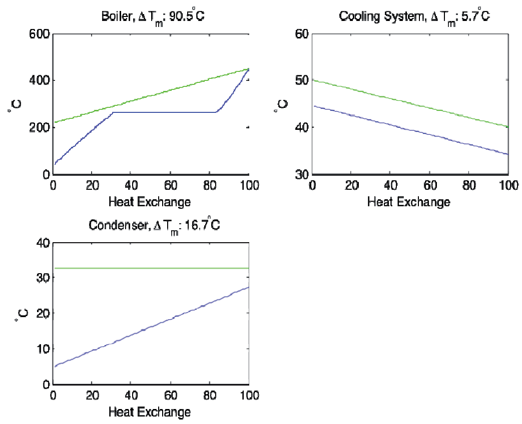


**Figure 9:** The temperature profiles of the Boiler, Cooling System and Condenser for the special steam Rankine cycle.

### 3.3 Organic Rankine Cycle

The setup of an Organic Rankine Cycle is a little bit more complicated than the steam Rankine design, but the thermodynamic relations are the same. Because of the saturation vapor curve of the organic fluid there is no need to set the constraint about the quality of the vapor exiting the turbine as the vapor always leaves the turbine in superheated state. A Organic Rankine cycle design proposed for heat recovery at Grundartangi is shown in Figure 7. The CS is included as a preheater after the condenser and before the recuperator.

Because the organic fluid is flammable a thermal oil loop must be implemented which isolates the working fluid from the furnace gas. This loop has thermal oil that flows through the furnace gas heat exchanger and then boils the organic fluid in another heat exchanger. The temperature of the thermal loop are set as close to the furnace gas temperature as the pinch allows, limited by the risk of condensation of sulphuric acid. The recuperator utilizes the vapor that exits the turbine to heat up the working fluid going to the boiler. The fluids selection for the ORC is in this study restricted to the fluids that are available in REFPROP. The most feasible one for these kind of temperatures is Toluene. It is also proven as working fluids in ORC applications [9].

*Optimization and constraints*

No heat- or friction losses are accounted for, efficiency of turbine is assumed 85% and efficiency of pump 50%. The objective of the optimization is to maximize the power output from the power plant by varying the optimization parameters, which are temperature and pressure after the boiler, the pressure and temperature after the turbine. The constraints are: 1) Pinch in heat exchangers cannot be less than 5°C but pinch in the recuperators is not less than 8°C; 2) Furnace gas temperature is fixed at 450°C down to 220°C; 3) The temperature of the water exiting the condenser is $T_D$=20°C; 4) The maximum temperature for the working fluid is 425°C and maximum pressure 50 bar.

*Results for ORC*

The highest net power output was 9.82 MW. In Figure 10 a T-S diagram of the ORC is illustrated and in Figure 11 the temperature profiles of the heat exchangers for the same system are shown. The optimum solution resulted in supercritical working cycle.The benefit of using the CS to preheat the working fluid is about 100 kW. The CS is better utilize by the ORC cycle than the steam Rankine because the temperature limit fits better into the system before the recuperator. One interesting result from the optimization is that the pinch in the boiler for the ORC configurations finds its optimum in the middle, as seen in Figure 11. Usually the pinch restriction will be at the exit of

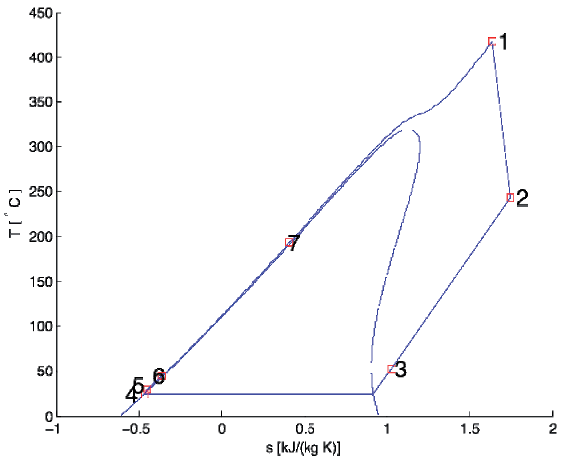

Figure 10: The TS diagram for Organic Rankine cycle

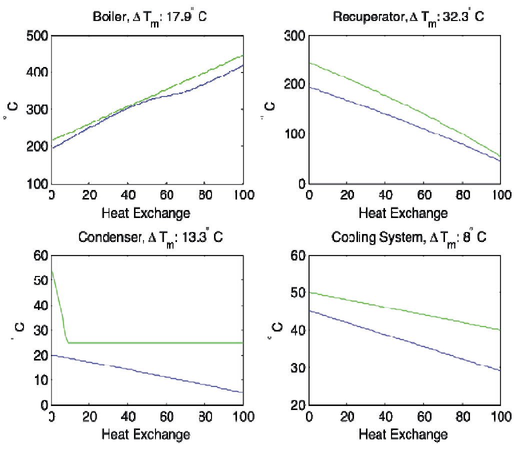

Figure 11: The temperature profiles of the boiler, cooling system, recuperator and condenser

the working fluid so the temperature is at maximum as seen in the temperature profile of the boiler in the Rankine cycles,Figure 9.

### 3.4 Steam Rankine vs. Organic Rankine

The optimal solution for the ORC produces about nearly 2 MW more net power than the steam Rankine cycle and the second law efficiency is about 13 % higher. The fact that the organic vapor leaving the turbine is superheated and that it can be used in a recuperator to heat up the fluid entering the boiler, gives the ORC a big advantage. The lower temperature of the furnace gas is restricted to 220°C and therefore the steam Rankine Cycle has to use this high temperature, and high quality energy, to heat the water in the working cycle from 45°C to the optimum point. The ORC on the other hand has its working fluid preheated with the recuperator and therefore the temperature of the fluid entering the boiler is much higher or about 193 °C and less of the quality of energy is lost. Another factor is that the ORC working fluid has lower critical pressure and temperature than the water and a supercritical power cycle is obtained within the pressure limits set in the optimization. If the boiler profile of the steam Rankine and ORC, Figures 9 and 11, are compared, it can be seen that the temperature of the ORC working fluid "follows" the furnace gas better that the steam. This leads to less entropy generation which is determined by the temperature difference of the two streams.

To get better utilization of the energy, changing the Cooling System should be evaluated as it could deliver higher quality energy. The temperatures in the CS are not even sufficient for districted heating purposes.

## 4 DISTRICT HEATING

From thermodynamic point of view heat is best utilized for heating purposes. This could be e.g. agriculture, fish farming, greenhouse heating, steam generation for industry and hot water generation for district heating schemes. There are two heat sources available, one in the cooling system (CS) and one in the furnace gas (OG). The CS is used to preheat the water and the OG then heats it up the temperature of the district heating which is 80°C. The same thermodynamic relations are valid as for the CS and OG in the Rankine cycle. The assumptions are following that the supply water for the district heating system is 5 °C, the district heating system design is 80/40/-10, that is the feedwater is 80°C, backwater is 40°C and the DH system is designed for maximum load at -10°C air temperature. The maximum mass flow obtained from furnace 3 at Elkem was 134 kg/s or 11800 $m^3$/day. It is obvious though, that a high entropy generation is taking place and exergy destruction will occour by producing hot water from high temperature furnace gas.

To put this Figures in perspective a closer look at Akranes, which is a town about 15 km from Grundartangi is performed. Akranes gets it hot water for district heating from Deildartunguhver, which is located about 75 km from Akranes.. The maximum load during the winter moths is 9000 $m^3$/day and therefore the hot water production from furnace 3 in Grundartangi could supply all the hot water needed by Akranes presently and in the near future.

## 5 CONCLUSIONS

In this study the potential for heat recovery at ELKEM Iceland ferrosilicon plant is evaluated using exergy analysis, power cycle simulation and district heating evaluation. The production of ferrosilicon involves large exergy destruction, estimated to be 46.5 MW, and the exergetic efficiency of the furnace is about 30 %. The energy analysis shows that much of the energy used in the production of ferrosilicon at Grundartangi goes out to the environment as waste heat. Only 35.6 MW of the 98 MW of the energy supplied to the process is retrieved as chemical energy in the product.

Evaluating electric power potential, the maximum net power produced with the steam Rankine cycle was about 8 MW. That was achieved by utilizing heat in the furnace gas and from the cooling system. But the low quality of the heat from the cooling system reduces the possibilities for using the heat. Only about 330 kW are used of the total 13 MW available in the cooling system. It would be possible to gain more power from the system if a superheater were designed into the furnace smokehood. The ORC configuration with Toluene as working fluid shows better performance than the steam Rankine cycle with a maximum net power about 10 MW.. The temperature range of the cooling system fits better to the ORC as a preheater before the recuperator and that leads to utilization of 940 kW of the heat, available in the cooling system.

Another option is to deliver water for district heating. Furnace nr. 3 at Elkem Iceland can supply about 11800 $m^3$/day of 80°C hot water for district heating. A nearby community, Akranes, uses district heating and the maximum load in the winter time never exceeds 9000 $m^3$/day. Therefore Elkem Iceland could easily supply all the hot water for Akranes using heat from one of its three furnaces.

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