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Research Article

Simulation and Design for Waste Heat Recovery in Electric Arc Furnace Metal Pools

Erdoğan Karip[1]*, Hakan F. Öztop[2], Gökhan Başman[3], Mesut Öztop[4], Serkan Öz[5], Hakan Coşanay[6,7], Cengiz Yaşin[8]

[1]Eti Krom INC., R&D Center, 23850, Elazığ- Türkiye
* **Corresponding Author Email:** erdogan.karip@etikrom.com - **ORCID:** 0000-0002-2679-1360

[2]Fırat University, Technology Faculty, Mechanical Engineering Department, 23119, Elazığ- Türkiye
Email: hakanfoztop@firat.edu.tr - **ORCID:** 0000-0002-2161-0639

[3]Eti Krom INC., R&D Center, 23850, Elazığ- Türkiye
Email: gokhan.basman@etikrom.com - **ORCID:** 0000-0001-8835-3641

[4]Malatya Turgut Özal University, Yeşilyurt Vocational School, 44900, Malatya- Türkiye
Email: mesutoztop@yahoo.com- **ORCID:** 0000-0003-1428-0448

[5]Eti Krom INC., R&D Center, 23850, Elazığ- Türkiye
Email: serkan.oz@etikrom.com - **ORCID:** 0009-0008-9938-4679

[6]Osmaniye Korkut Ata University, Fac.of Eng. and Natural Sciences, Dep.of Energy Systems Eng. Osmaniye- Türkiye
[7]Osmaniye Korkut Ata University, Specialization Coord. of Renewable Energy and Battery Tech., Osmaniye-Türkiye
Email: hakancosanay@osmaniye.edu.tr- **ORCID:** 0000-0002-5299-2078

[8]Eti Krom INC., R&D Center, 23850, Elazığ- Türkiye
Email: cengiz.yasin@etikrom.com - **ORCID:** 0000-0005-7964-3408

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Abstract:

A significant amount of waste heat is generated in the metal pools during the production of high carbon ferrochrome in electric arc furnaces. This waste heat manifests itself in the form of heat emitted to the atmosphere from the metal pools and the temperature of the flue gases. Although there are many studies on waste heat recovery from flue gases, there is limited research on waste heat recovery in metal pools. In this study, the recovery of waste heat generated in metal pools in ferrochrome production at Eti Krom INC., the world's largest producer of hard piece chromium, was investigated. The product produced during ferrochrome production is left to cool in metal pools. The initial temperature of ferrochrome metal, which starts to cool in the pools, is between 700-800 °C. In this context, the proposed system consists of heating the water circulating in the pipe from 15-20 °C to 85-90 °C by utilising the waste heat with the heat exchanger system mounted under the metal pools. Different numerical simulations have shown that the designed system can successfully heat water to 85-95 °C by utilising waste heat. Economic analyses were made for the designed system to be obtained by energy recovery from waste heat. As a result, it was determined that the energy required to raise 10 m^3 of water from 15 °C to 85 °C with this system is 813 kWh energy and this energy is equivalent to 195 kg coal or 91 m^3 natural gas consumption. In addition, the recovery of waste heat in the metal pools through this system significantly reduces waste heat and carbon emissions in the atmosphere by reducing fossil fuel consumption.

1. Introduction

The Industrial Revolution and its consequences have been a disaster for the human race and global climate change [1]. Looking at the global warming data, it is seen that the atmospheric temperature changes in the range of 0.75-1.5 degrees. A one degree increase in average temperature as a result of global warming causes many different climate crises. Therefore, the target of 1.5 degrees against global warming has emerged. This has resulted in a very serious sanction decision by the European Union (EU). In this respect, the EU has established the 'A European Green Deal (EGD)' framework with the approach of turning an urgent crisis into an opportunity for its countries and citizens. The European Green Deal is a new growth strategy that aims to transform the countries of the EU into a just society with a resource-efficient and competitive economy with no net greenhouse gas emissions by 2050. The EGD is a new initiative born on the green economic order as a supporter of the Kyoto Protocol in the past and the Paris Agreement in the current conjuncture [2]. Within the scope of EU adaptation policies, the EGD, which has transformed from environmental sanctions to economic sanctions, has forced the sectors to transform their production systems in order to ensure decarbonisation during the production of exported products and these products, primarily for the iron and steel, aluminium, cement, plastic, chemical and agricultural sectors [2, 3].

In the industry, iron and steel sector is one of the leading sectors where both carbon emissions are the most intense and the waste heat generated is emitted to the atmosphere and causes global warming. Blast furnaces and electric arc furnaces (EAF), which are widely used in the iron and steel industry, cause a very high amount of waste heat. Liu et al [4] conducted an experimental study to reuse waste energy from molten metal slags. In the study, solid particle diameter and size distribution of metallurgical slags with different viscosity and surface tension were investigated by dry granulation. The results showed that the molten slag bond length was high in granulation for slag of iron alloys with high viscosity. For metal slag with low viscosity and surface tension, the increase in rotational speed causes a small change in the average diameter of the solid particles. The study conducted by Zuo et al [5] focused on the recovery of precious metals and waste heat from copper slag. They emphasised that metal extraction and waste heat recovery should be performed simultaneously before using Cu slag as a material source. Congedo et al [6] conducted a study on the efficiency and energy behaviour of Ground Source Heat Pumps (GSHP) used for heating and cooling of buildings. The results indicate the heat fluxes transferred to and from the ground and the efficiency of the system. Cao et al [7] investigated the heat pipe heat exchanger used for waste heat recovery in slag cooling process in steel industry. The main parameters representing the heat exchanger were investigated experimentally and theoretically and the optimum operating conditions were determined by the first and second laws of thermodynamics. The results show that the heat transfer rate and heat transfer coefficient increase with the water flow rate. Jouhara [8] designed and tested a straight heat pipe heat exchanger for the recovery of high temperature heat released in steel production. The thermal performance and heat transfer rate of the designed heat exchanger were investigated. The results show that the heat transfer capability of the system is strongly affected by the temperature of the high temperature source. Chang, [9] modelled the coke production process in iron and steel industry with waste heat recovery. Real plant data were compared with literature data, coke production process based on quench mode and waste heat recovery was analysed by three methods: thermodynamic, techno-economic and CO_2 emission analysis. As a result of the studies, it was determined that energy and economic efficiency will increase and CO_2 emissions can be reduced with waste heat recovery. Similar studies on waste heat recovery systems are found in the literature [10, 11, 12].

Blast furnaces and electric arc furnaces (EAF) used in industry increase carbon emissions through electricity consumption, natural gas consumption or fossil fuel consumption. Electric arc furnaces are also used in the production of high carbon ferrochrome (HC FeCr). HC FeCr is briefly produced by feeding chromite ores to the furnace and reducing in the EAF using coke. The HC FeCr produced is then taken to the metal pools. Reduction reactions of chromium concentrates depending on temperature are shown in Figure 1 [13, 14].

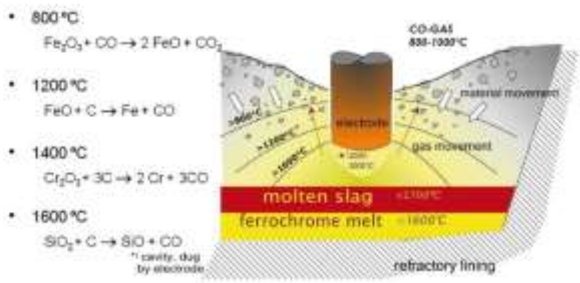

Figure 1. *Reaction zones in an electric arc furnace [13, 14]*

The initial temperature of HC FeCr in the metal pools is 700-800 °C and it is kept in the metal pool for 24 hours. This situation leads to a high amount of heat release to the atmosphere and there is no study in the literature for the recovery of this heat.

In this study, the recovery of waste heat generated in metal pools in ferrochrome production at ETİ KROM Inc., the world's largest producer of hard piece chromium, was investigated. In this context, the proposed system consists of heating the water circulating in the pipe from 15-20 °C to 85-90 °C by utilising the waste heat with the heat exchanger system mounted under the metal pools. Different numerical simulations have shown that the designed system can successfully heat water up to 85-95 °C using waste heat.

2. Material and Methods

Ferrochrome (FeCr) is a ferroalloy which includes iron and chromium. Depending on the application, ferrochrome contains between 50-70% chromium. It comes from the reduction of chromite, a mineral composed mainly of chrome oxide and iron oxide and mined as chrome ore. Ferrochrome is the most important intermediate raw material for the production of stainless steel and uses the majority of the world's chrome supply. High carbon ferrochrome (HC FeCr) contain between 4% and 9% of carbon, and the difference between these two is essentially in chromium and silicon content. HC FeCr typically contains 60-70% in chromium content and 1-3% silicon.

HC FeCr can be produced by a blast furnace method, an electric furnace method, and a plasma furnace method. The most common modern method of production of HC FeCr with high chromium content is smelting in submerged electric arc furnaces. The basic principle of electric furnace smelting of HC FeCr is to reduce chromium and iron oxides with carbon. The schematic diagram of HC FeCr production is given in Figure 2.

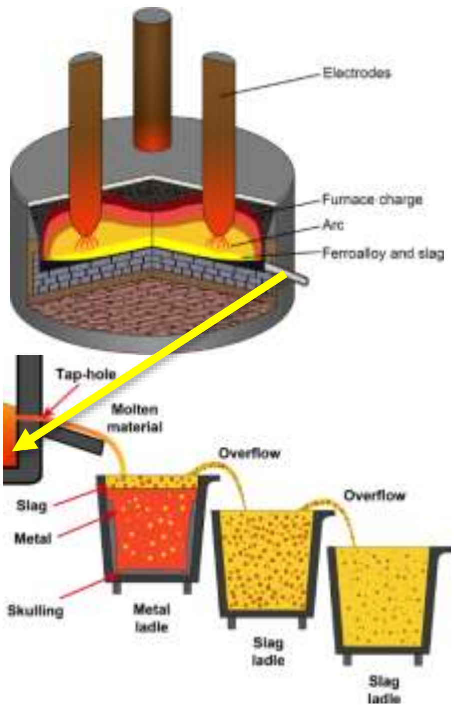

Figure 2. *Schematic diagram of HC FeCr production in an EAF [15]*

The completed HC FeCr metal is separated into slag and metal. It is then allowed to cool for 24 hours in HC FeCr metal pools. HC FeCr metal, which cools under atmosphere, is taken to the stock area as a saleable product after two-stage crushing process. Figure 3 shows the images of ETİ KROM Inc. HC FeCr production. The experimental studies are based on the metal pool given in the image. A schematic diagram of the experimental design is given in Figure 4.

Figure 3. *HC FeCr production in EAF of Eti Krom Inc.*

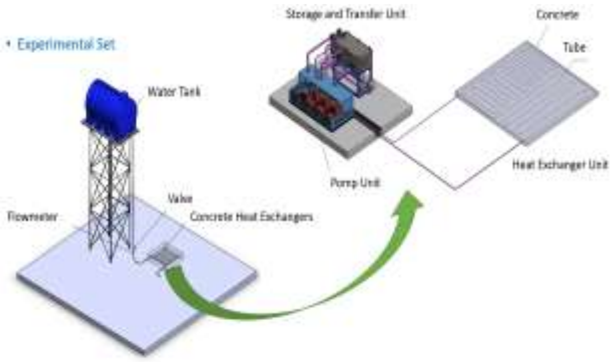

Figure 4. *Schematic diagram of the experimental design*

The experimental design mainly consists of a water tank, a flow meter with valve and a heat exchanger system embedded in the metal pool. The operation of the experimental setup is briefly taken into the HC FeCr metal pool melted in EAF. The water leaves the tank at 15-20 °C and passes through the heat exchanger system buried under the metal pool. The heat of the metal in the pool is used to heat the water passing through the heat exchanger by conduction. The heated water (80-85 °C) coming out of the heat exchanger is used to meet the hot water needs of bathrooms, kitchens, etc. in the factory. Images of the experimental set prototype are given in Figure 5.

Figure 5. *Images of the experimental set prototype*

3. Results and Discussions

Experimental studies consist of two stages. In the first part, simulation studies were carried out using ANSYS (Swanson Analysis Systems) programme. The experimental set was established with reference to the simulation data. In the second part of the experimental studies, experiments were carried out in the laboratory scale experimental set. In the experimental studies, the heat exchanger pipe diameter was simulated as 1 and 1.5 inch and the initial temperature was simulated as 700 °C and 800 °C. A visual of the inputs used in the ANSYS simulation programme is given in Figure 6. Table 1 show the values obtained for 1 inch and 1.5 inch pipe diameter, respectively. In addition, the reference data values used in ANSYS are given in Figure 7. HC FeCr metal releases a heat of about 800 °C at the first casting. This heat radiates into the atmosphere and increases the global atmospheric temperature. Simulation studies have shown that 10-15 °C water can be heated above 70 °C by using this waste heat

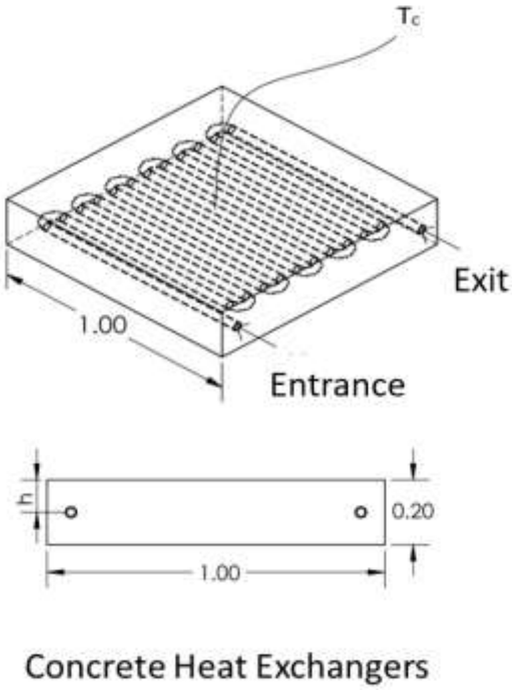

Figure 6. *Reference data values used in ANSYS programme*

Table 1. *Simulation data for pipe diameter 1.5 inch*

	Entrance Speed (m/s)	Flow Rate (kg/s)	h (m)	Exit Temperature (°C)
T_c=800 °C	0.5	0.678	0.10	21.21
	0.1	0.135	0.10	42.52
T_c=700 °C	0.5	0.678	0.10	20.84
	0.1	0.135	0.10	38.82

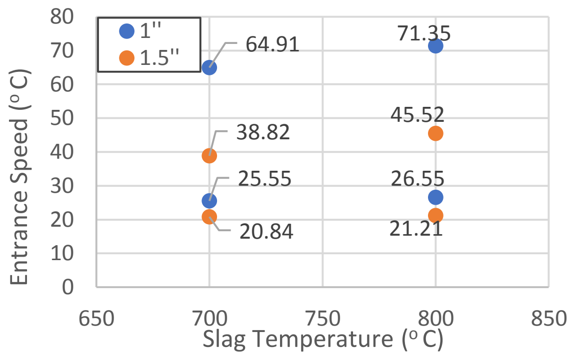

Figure 7. *Average outlet temperature graph according to pipe diameter and slag temperature*

with the experimental setup. Hot water used in bathrooms, kitchens, etc. is generally in the range of 60-70 °C [16]. ANSYS simulation studies have shown that this water can be used successfully. ANSYS programme results are given in Figure 8.
The parameters studied in the ANSYS simulation programme were evaluated in terms of pipe diameter, positioning of the pipe height in concrete (h), and average slag temperature (Tc).

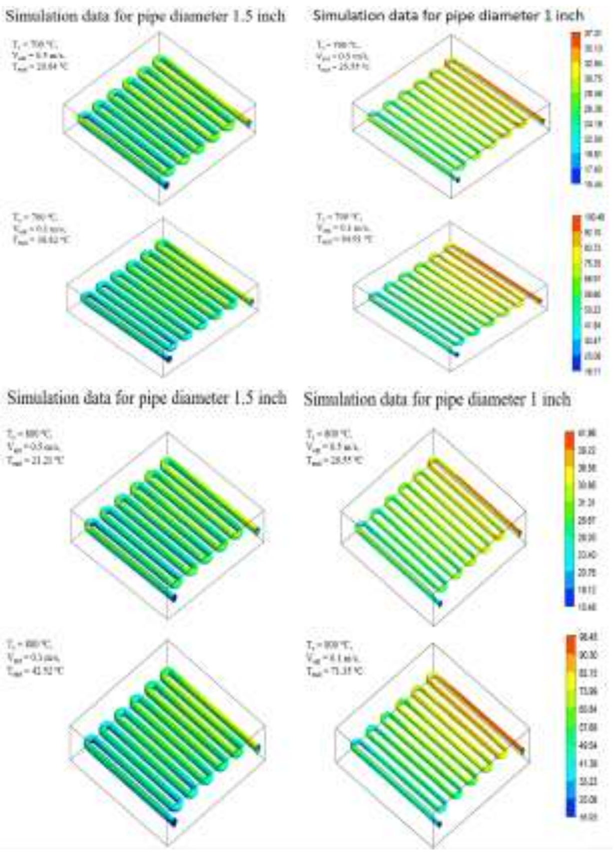

Figure 8. *ANSYS simulation outputs for 700 °C and 800 °C temperatures, respectively*

In the analyses, the water inlet temperature was assumed to be constant and 15 °C. The results obtained show that the outlet temperatures increase as the pipe diameter and inlet velocity decrease. Any situation foreseen from the studies carried out has shown that it can be used as a prototype for field trials. In addition, when the simulation analysis results are examined, it is recommended to use 1.5 inch pipe diameter for 0.1 m/s water velocity and 1 inch pipe diameter for 0.5 m/s water velocity. The test prototype was designed in the light of these data. An experiment set was installed in ETI KROM/R&D Metallurgy Laboratory. During the experimental studies, the inlet temperature of the water entering the heat exchanger was monitored with 1 thermocouple and the outlet temperature of the water leaving the heat exchanger was monitored with 2 thermocouples. The temperatures of the water entering and leaving the heat exchanger were measured with a HIOKI data logger. The data obtained with the data logger in the experimental studies are given in Figure 9. The data logger is capable of measuring 15 thermocouples. During the experimental studies, a thermocouple was installed at inlet 2-1 to measure the temperature of the water entering the heat exchanger, and thermocouples were installed at inlets 2-3 and 2-4 to measure the temperature of the water leaving the heat exchanger.

Figure 9. *Input and output temperature values obtained with the data logger*

ANSYS simulation programme, it was analysed that the temperature could reach 85-95 °C. However, experimental studies showed that water can be heated to 50-60 °C with waste heat recovery. In fact, this temperature meets the required water temperature in the bathroom or kitchen [16]. This result observed in the experimental study can be explained as follows. During HC FeCr production, 0-5 mm metal salt is laid on the bottom of the metal pool. This metal powder is thought to prevent heat conduction. In addition, the concrete (C 25/30) used in the metal pool design also reduced the heat conduction and had a negative effect on the further heating of the water. These problems can be solved with a few simple revisions.

During the cooling process of HC FeCr metal, a heat energy of approximately 875,000 W is released into the atmosphere. During the production of HC FeCr at ETİ KROM, metal casting is carried out nine times in 24 hours and there is a heat energy loss of approximately 236,250 kW on a monthly basis [17]. In addition, 292,740 J of heat energy is required to heat 10 m^3 of water from 15 °C to 85 °C. To obtain this heat energy, an energy consumption of approximately 813 kWh is required. To obtain 813 kWh of energy, 195 kg of coal and 91m^3 of natural gas consumption is required [18]. For this reason, providing energy recovery with a heat exchanger system embedded in concrete in facilities with similar waste heat loss will both prevent the release of waste heat to the atmosphere and prevent carbon emissions by reducing the consumption of fossil wastes required. For these reasons, the study can be successfully applied in sectors where similar heat losses are in question, especially in the iron and steel sector. As a result, this study has both met the expectations of the industry within the scope of the European Green Deal and brought a new perspective to industry-university collaborations in terms of ensuring green transformation of industries at very low costs.

4. Conclusions

- The design, prototype production, pilot application and testing processes of the heat exchanger system embedded in concrete proposed for metal pools constitute the R&D stages of the project.
- It is planned to utilize the waste heat generated in the metal pools and use the hot water to be obtained within the needs, ***reducing costs*** and ***reducing the carbon footprint***.
- It is aimed to release lower degrees of heat to the ***atmosphere by ensuring the reuse of waste heat.***
- Simulation studies have shown that ***195 kg of coal*** and ***91 m^3 of natural gas*** consumption will be prevented if the waste heat in the metal pools is increased from 15 °C to 85 °C for 10m^3 of water.
- Experimental studies have shown that water can be raised to ***50-60 °C*** by utilizing waste heat.
- Efficiency can be increased by adjustments such as concrete thickness, metal powder thickness, etc.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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