THE APPLICATION OF ORC SYSTEMS FOR WASTE HEAT RECOVERY IN METAL SMELTING INDUSTRY

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ABSTRACT

The metal smelting industry is characterized by significant emission of waste heat. This applies to both ironworks and non-ferrous smelters. In various technological processes related to the processing of metal ores, waste substances (in the form of liquids and gases) are released. These include cooling water and oils, slag disposal, throat gas, blast furnace gas, converter gas and other waste gases. Significant amounts of waste heat are also emitted from smelting products (castings, etc.). At different stages of metal production, different waste heat carriers are emitted at the different temperature and capacity levels. The assessment of the applicability of the heat source for the heat recovery requires a multi-aspect analysis of the heat source's characteristics as well as chemical aggressiveness and contamination of the carrier. In many cases, waste gases are containing components which are harmful and aggressive to construction materials. Moreover, the capacity of these gases is often floating.
Due to the high power of waste heat sources generated in metal processing industries, ORC systems are promising for heat recovery application. The article presents an analysis of the applicability of ORC systems for waste heat recovery in this branch of industry. The output and thermal characteristics of generated waste heat sources are comprehensively discussed in first part of this paper. The thermal power of these sources is then determined and the calculation models of ORC systems dedicated to waste heat recovery from these sources are proposed. Model calculations were carried out and the results of modelling on the ORC systems operating parameters and their performance are presented in this article. Modelling was carried out for various working fluids with a vaporization temperature appropriate for the temperature range of the different heat sources. The results of the analyses indicate that the potential of waste heat sources generated in smelting industry is significant and ORC system is a promising technology for application in this branch of industry.

1. INTRODUCTION

Ferrous and non-ferrous metals (such as copper, lead, aluminum, zinc, etc.) are used practically in all areas of human activity as basic construction materials. Demand for high-quality metals is growing along with the technological and economic development of societies and the growing demand for various products in which these metals are used. The metal processing industry is thus one of the most important fields of the global economy (according to Ortiz-Ospina et al. in 2018 metal ores mining has 4.6 % share in global export while metal products have 2.0 % share in global export. Metallurgical processes are usually carried out in stages in specially designed furnaces and devices, differing depending on the type of metal produced and the type of the smelter (production, processing or recycling). The metal processing is a high energy consuming. In addition to furnaces where exothermic reactions take place (e.g., flash smelting furnace) and fuels are used only to support the ongoing process, metallurgy uses numerous aggregates in which the heat used in the process is obtained by burning fuels (oil, nitrogen-rich gas, coal and others). Fuels are also used in a number of

auxiliary processes (such as e.g., ore drying). Some of the devices (such as an electric furnace) use electricity to heat the charge. In all stages of the metal processing, it is necessary to provide cooling of the furnaces (using various fluids such as e.g. oil, cooling water or air) and to draw off large quantities of high temperature waste gases from the process. Some of these substances can be treated as waste heat carriers that could be recovered. Szargut (1983) indicated that the share of wasted heat in metallurgical processes is large and, depending on the type of process, ranges up to 70 % of the energy supplied to the process. Szargut (1983) clearly visualized the energy flow in the iron blast furnace on the Sankey chart, which is presented in Figure 1.
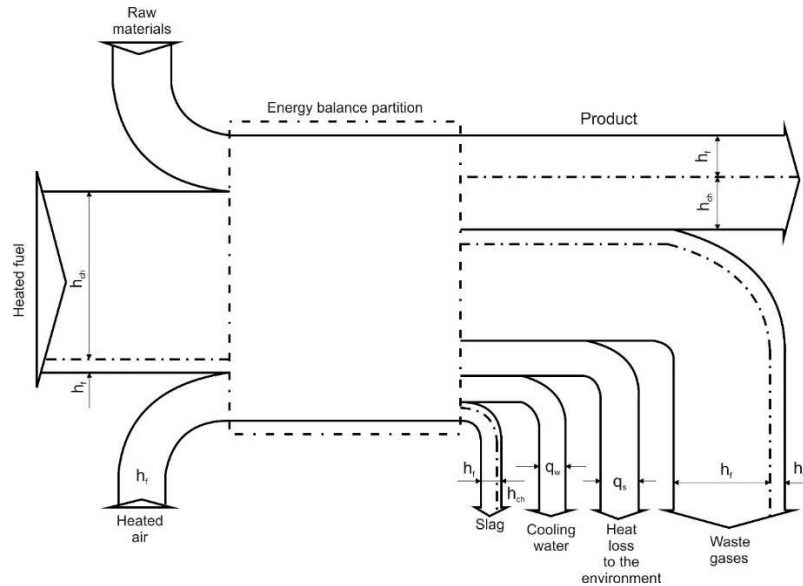

Figure 1: Energy flow in the iron blast furnace (adapted from Szargut)

Table 1: Waste heat carriers generated in the processing of iron and aluminum ore (according to U.S. Department of Energy)

Industry	Waste heat carrier	Average temperature range, °C
Iron and steel	Coke Oven Gas	980 °C
	Coke Oven Waste Gas	200 °C
	Blast Furnace Gas	430°C
	Blast Stove Exhaust	250 °C (No recovery) 130 °C (With recovery)
	Basic Oxygen Furnace	1700 °C
	Electric Arc Furnace	1200 °C (No recovery) 200 °C (With recovery)
	Hot Coke	1100 °C
	BF Slag	1300 °C
	BOF Slag	1500 °C
	Cast Steel	1600 °C
	Hot Rolled Steel	900 °C
Iron Cupola		900 °C (No recovery) 204 °C (With recovery)
Aluminum	Hall Heroult Cells	700 °C
	Secondary melting	1150 °C (No recovery) 538 °C (With recovery)
Aluminum Casting	Reverb Furnace	1150 °C
	Stack smelter	121 °C

It should be pointed out that in such a large industrial plant as the steelworks and non-ferrous smelters the variety of the type of waste heat carriers, their output and temperature is very high. Not all of these substances can be used in a technically or economically justified way. Their suitability for use depends mainly on the level of temperature and output. As indicated by U.S. Department of Energy these carriers differ depending on the type of metallurgical process. In the metallurgy of iron, steel and aluminum the substances listed in Table 1 are mentioned as the main waste heat carriers.

Waste heat transferred by these carriers is used in a variety of ways. One way is to recuperate and use this heat to preheat the substrates of the process such as air, fuels, feed and other substances. In some cases, from waste gases, the heat is partially recovered in recuperators or waste heat recovery boilers for the generation of steam for technological purposes (or for generating electricity in steam turbines). In many cases, however, this heat is uselessly transferred into the atmosphere. One of the technologies enabling the processing of waste heat into high-quality energy products such as electricity, heat (central heating or technological), and cold are steam power plants and ORC systems. Generated electricity, heat or cold can then be used to cover the own needs of the factory or can be used by external consumers.

The pyrometallury of copper is one of the most complicated and energy intensive metallurgical process. For these reasons it was selected for further, comprehensive analysis. Therefore, the possibility of using ORC systems for waste heat recovery in a copper smelter was analyzed. The main furnaces and devices used in this process were analyzed and the waste heat carriers were identified. Then, based on the adopted assumptions regarding the ORC system power, the working medium used and the efficiency of the subassemblies the calculations of technical parameters of ORCs were carried out for the different waste heat sources.

2. IDENTIFICATION OF THE WASTE HEAT CARRIERS GENERATED IN THE PYROMETALLURGY OF COPPER

According to Kucharski (2003) and Piestrzyński et al. (2008) the copper smelting process is a multi-stage process, conducted in a sequence of the following processes taking place in various metallurgical furnaces and devices (see, Figure 2 adapted from www.ppcu.co.jp).
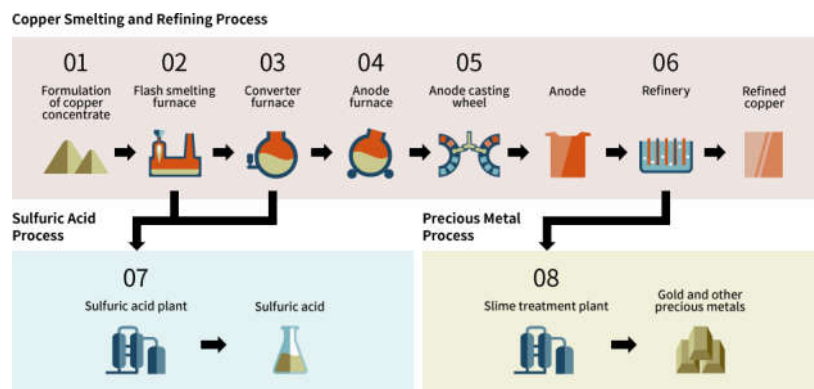

Figure 2: The scheme of the copper smelting and refining process (adapted from www.ppcu.co.jp)

Initially the ore concentrate is prepared for smelting, i.e. it is mixed, averaged and dried. Then, the ore concentrate is smelted in flash furnace to blister copper (99% Cu). During this process, in addition to blister copper, the slag is obtained, which is then treated in electric furnace and converter furnaces in order to obtain waste containing as few metals as possible. Then, refining of blister copper to remove impurities in rotary and stationary furnaces and casting of the anodes is proceeded. At last, anodes are electro-refined. During this process the anode copper dissolves in the electrolyte and settles on the cathode, which contains 99.99% Cu. These processes are described in more details in the following paragraph.

After mining in the mine, copper ore is appropriately prepared for further technological processes. In order to achieve the appropriate chemical composition, the concentrate is averaged and mixed. The

first stage of its heat treatment is drying. Drying is carried out in a dryer in which the concentrate can be dried using various gases (it can be, for example, steam, heated air or exhaust gas).

After drying, the concentrate is directed to a flash furnace where it is burnt in a concentrate burner. The reaction carried out in the flash furnace is exothermic reaction. It is only supported by the heat obtained from burning the heating oil. According to Kojo (2006) as a result of this reaction, the concentrate is melted and formed this way liquid blister copper is collected as the bath in hearth of the flash furnace. In addition to the blister copper, the process also produces slag, which is then treated in an electric furnace. During the process carried out in a flash furnace, large amount of waste gas is released at temperatures above 1000 °C. This gas is at the furnace outlet highly contaminated with volatile fractions (dust) and sulfur compounds. The gas is then cooled and dedusted in a waste heat boiler, where waste heat contained in the gas is used to evaporate water and produce steam, which can be used for technological purposes or for driving the turbine that can be used to drive feeding pumps or a current generator. At the outlet of the waste heat boiler the temperature of waste gas drops to ca. 350 °C. Then, the gas is cleaned in electrostatic precipitators and is flowing through the pipelines to the sulfuric acid plant. The shaft casings of the flash furnace are cooled using water and the heart is air-cooled. The temperature of these cooling mediums is too low to be applied for powering the ORC systems. The next device of the technological chain is an electric furnace. In the electric furnace, the treatment of the slag is proceeded. The slag is poured into the electric furnace from the flash furnace through a set of tapping runners. According to the literature its temperature is around 1200—1250 °C. After filling the electric furnace, the process of heating the batch begins. To this end, Sodeberg's self-sintering electrode assembly is used. During the treatment, the alloy composed of copper and other metals is obtained. The alloy is poured from the electric furnace and poured into the converter and anode furnaces. The high-temperature waste slag is remaining in the electric furnace after the process and it is poured from the furnace by a system of tapping runners and granulated in a water-cooled granulation system. The casing and the roof of the electric furnace are cooled with water and the heart is air-cooled. During the process of the slag treatment in an electric furnace, large amounts (up to several hundred thousand cubic meters per hour) of high-temperature (ca. 950-1350 °C) waste gas are released. This gas is then burned in the after-burning chamber and cooled in an atmospheric cooler.

The next stage of copper thermal processing are processes carried out in converters and stationary and rotary anode furnaces. The charge for rotary anode furnaces is a liquid blister copper and liquid blister copper. The heat is supplied to the furnaces thanks to the combustion of the nitrogen-rich gas. Processes carried out in rotary anode furnaces are cyclical. The full cycle of the furnace consists of the phase of flooding, reduction and casting of the anodes. The waste heat carriers generated during processing of the liquid charge in rotary anode furnaces are primarily high-temperature waste gas (which is combusted in the post-combustion chamber) and water used for cooling the post-combustion chamber. The temperature of the waste gases on the outlet of the post-combustion chamber is about 720 °C. In the case of stationary anode furnaces, the charge may be liquid or solid. As in the case of rotary anode furnaces, the processes carried out in stationary anode furnaces are cyclical. Stationary anode furnaces also utilizes heat of combustion of nitrogen-rich gas as the heat source. The waste heat in stationary anode furnaces is mainly carried in the high-temperature (ca. 890 °C) waste gases and cooling water. The waste gases from stationary and rotary anode furnaces are contaminated, thus they are directed to the flowing to cooling, purification and deashing system. The mean temperature of the gas at the inlet to this system ranges between 300 °C and 340 °C. Purified and cooled gas is then discharged into the atmosphere.

As it results from the above considerations, the most interesting (in terms of the thermal potential and output) waste heat carriers possible for application to ORC system powering are waste gases from the electric furnace and from anode furnaces. Their thermal parameters are summarized in Table 2.

The availability of the flue gases, depends mainly on type of the furnace, its characteristic and operating dynamics which in many cases results in floating thermal and output characteristic of the ORC system heat source. Therefore, the ORC systems have to adapt to changing conditions of the heat supply which causes difficulties in their design.

The further part of the article reports the results of modelling of the ORC system adopting different working fluids with the assumption of its powering by the waste heat obtained from waste gases generated in copper smelter.

Table 2: Thermal parameters of waste gases generated in the processing of copper ore (according to Kucharski and Piestrzyński et al.)

Device	Average Temperature range and thermal power range
Flash furnace	Outlet of the furnace: 1350 °C Outlet of the waste heat recovery boiler: 360-410 °C Average thermal power range: 1-2 MW
Electric furnace	Outlet from the furnace: 950-1350 °C Inlet to the cooler: 285 °C Outlet of the cooler: 75-121 °C Average thermal power range: 1.5-3 MW
Rotary anode furnace	Outlet of the post-combustion chamber ca. 720 °C Inlet to the cooling, purification and deashing system ca. 240-300 °C Average thermal power range: 1.5-2 MW
Stationary anode furnaces	Outlet of the post-combustion chamber ca. 890 °C Inlet to the cooling, purification and deashing system ca. 90-200 °C Average thermal power range: 1.5-2 MW
Cooling, purification and deashing system	Inlet to the system 90-300 °C Average thermal power range: 1-3 MW

3. MODEL OF THE ORC SYSTEM AND MODELLING ASSUMPTIONS

For further analysis, the evaporative ORC with regenerative heating of the liquid supplying the evaporator was modelled. The schematic and T-s diagram of this system are presented in Figures 3a and 3b respectively.
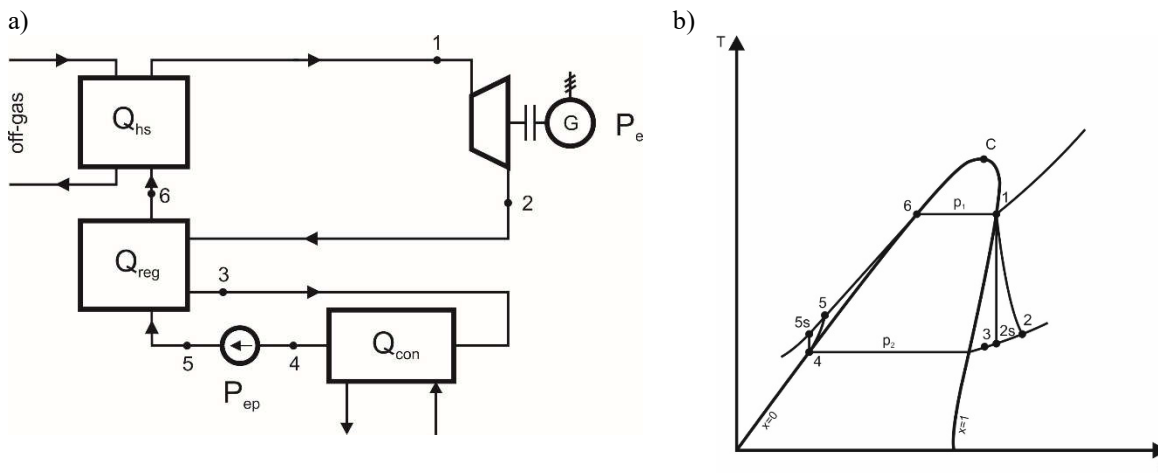

Figure 3: Modelled ORC system
a) The scheme of the modelled ORC system, b) T-s diagram of the ORC system

The main components of this system are: the evaporator, the regenerator, the expander, the working fluid pump and the condenser. Similar models are applied for calculations related to industrial ORC systems and were used by Rettig and Müller (2015).
The mathematical model of the system was based on the energy balance, for the fixed electrical power of the system. The electrical power of the ORC system can be obtained from the equation

$$P_e = \dot{m} \cdot (h_1 - h_2) \cdot \eta_{exm} \cdot \eta_{exe} \tag{1}$$

where m is the mass flow of the working fluid, h_1 and h_2 is the specific enthalpy of the working fluid at the inlet and the outlet of the expander respectively, η_{exm} is the mechanical efficiency of the expander, η_{exe} is the electrical efficiency of the generator.

The internal efficiency of the expander can be obtained from the equation

$$\eta_i = \frac{h_1 - h_2}{h_1 - h_{2s}} \tag{2}$$

where h_{2s} is the enthalpy at the outlet of the expander if isentropic expansion is considered.

The electrical power of the ORC system pump can be obtained from the equation

$$P_{ep} = \frac{\dot{m} \cdot \left(h_5 - h_4 \right)}{\eta_{pm} \cdot \eta_{pe}} \tag{3}$$

where h_5 and h_4 is the specific enthalpy of the working fluid at the outlet and the inlet of the pump respectively, η_{pm} is the mechanical efficiency of the pump, η_{ee} is the electrical efficiency of the motor driving the pump. The power of the ORC system regenerator can be obtained from the equation

$$Q_{reg} = \dot{m} \cdot \left(h_6 - h_5 \right) \tag{4}$$

where h_6 and h_5 is the specific enthalpy of the working fluid at the outlet and the inlet of the regenerator respectively.

The efficiency of the ORC system can be obtained from the equation

$$\eta_{ORC} = \frac{P_e - P_{ep}}{\dot{m} \cdot \left(h_1 - h_6 \right)} \tag{5}$$

where h_1 and h_6 is the specific enthalpy of the working fluid at the outlet and the inlet of the evaporator respectively.

It was assumed that the electrical power of the ORC system will be equal to 1000 kW and that (from the technical reasons, such as e.g. providing the optimum conditions of purification system operation) the waste heat can be recovered from waste gases at the temperature range of 350—100 °C. The internal efficiency of the expander is dependent on many conditions, such as e.g., expander design, working fluid flow rate, expansion ratio, enthalpy drop in the machine, etc. For this treatment the internal efficiency of the expander of $\eta_i = 75$ % was assumed, basing on the data reported by Andreasen et al. (2017). The assumptions adopted for the modelling are summarized in Table 3.

Table 3: The assumptions adopted for the ORC system modelling

Variable	Value
Electrical power of the ORC system	$P_e = 1000$ kW
Waste gases temperature	$t_{hs} = 350—100$ °C
Cooling fluid temperature in the condenser	$t_{con} = 20$ °C
Internal efficiency of the expander	$\eta_i = 75$ %
Internal efficiency of the system pump	$\eta_{ip} = 80$ %
Mechanical and electrical efficiency of the system pump	$\eta_{pm} \cdot \eta_{pe} = 85$ %

The working fluid selection is key issue of the ORC system design. The choice of working fluid can be done on the basis of the different criteria (e.g., toxicity, GWP, ODP, corrosivity or thermal properties). For this analysis the working fluids were selected on the basis of their thermal properties i.e. the critical and condensing temperature which were then compared to the temperature of the waste

heat source (waste gases). The criterion of the working fluid selection was ensuring that the highest temperature of cycle would not exceed the critical temperature of the working fluid. On this basis, the substances that could be applied as working fluids in the considered ORC system were selected from the CoolProp database. The following substances were selected for modelling analysis: acetone, benzene, cyclopentane, cyclohexane, heptane, isohexane, isopentane, MD2M, MD3M, MDM, methylcyclohexane, MM, nonane, octane, pentane, perfluoropentane, propylocycleohexane, R113, R114, R115, R123, R124, R141b, R245ca, R365mfc and toluene. The modelling was proceeded for the following temperatures of the heat source 350 °C, 300 °C, 250 °C, 200 °C, 150 °C and 100 °C. For each of these cases the efficiency of the system was calculated as the main assessment criterion.

4. MODELLING RESULTS

Figure 4 summarizes the results obtained by modelling and visualizes the variation of the modelled ORC system efficiency vs the temperature of the heat source and the type of the working fluid.. As can be seen from this Figure, the efficiency of the ORC system decreases as the temperature of the heat source (i.e. waste gases) decreases for all of the analyzed working fluids.
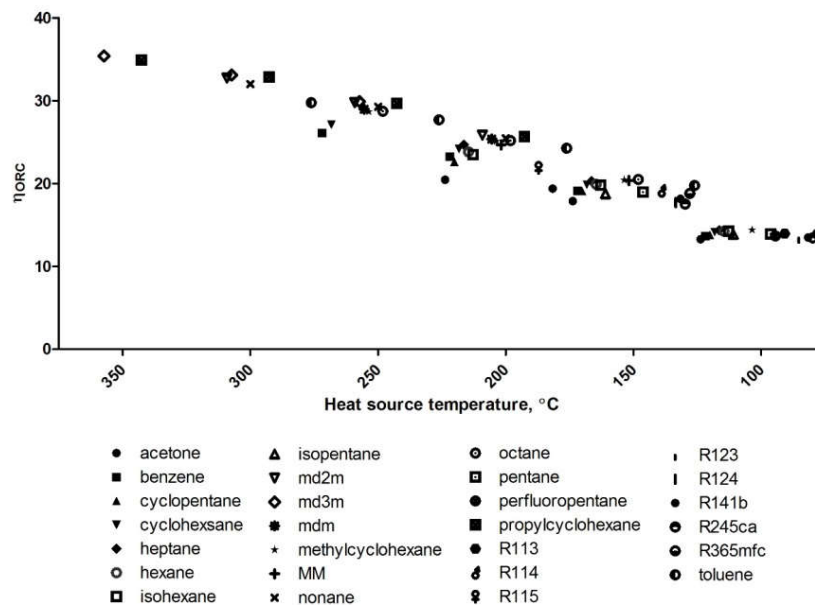

Figure 4: The variation of the modelled ORC system efficiency vs the temperature of the heat source for different working fluids

The highest efficiency values of 35.5 and 35% were obtained adequately for MD3M and propylcyclohexane for a heat source temperature of 350 °C.

For a heat source temperature of 300 °C, the highest efficiency values of ca. 33% were obtained for the same working fluids. For MD2M, the obtained efficiency was ca. 32.7% and for nonane, ca. 32%. The lowest efficiency of ca. 29.8% was obtained in this temperature range of the heat source for toluene.

For a heat source temperature of 250 °C, the highest efficiency values of ca. 30% were obtained for MD3M. For MD2M and propylcyclohexane, the obtained efficiency was ca. 29.8 %. Efficiency values of 28.6—29.3% were obtained for methylcyclohexane, acetate, MDM and nonane. Efficiencies of 27.2 and 27.7% were obtained for cyclohexane and toluene, respectively. The lowest efficiency of approx. 26.1% was obtained in this temperature range of the heat source for benzene.

For a heat source temperature of 200 °C, the highest efficiency values of ca. 25.1-25.9% were obtained for methylocyclohexane, octane, MDM, nonane, propylcyclohexane and MD2M. Efficiencies from the range of 24.2-24.7% were obtained for cyclohexane, toluene, MM and heptane. Efficiency from the range of 23.3 and 23.8% was obtained for benzene, isohexane and hexane. For the

cyclopentane, an efficiency of ca. 22.6% was obtained, and for R115 an efficiency of ca. 21.9% was obtained. Efficiency of 20.5% was obtained for acetone. The lowest efficiency of ca. 19.4% was obtained in this temperature range of the heat source for R141b.

For a heat source temperature of 150 °C, the highest efficiency of ca. 20.3—20.5 % was obtained for heptane, MM, methylocyclohexane and octane. Efficiencies from the range of 19.0-19.9% were obtained for pentane, cyclopentane, R114, benzene, toluene, isohexane, cyclohexane, and hexane. Efficiencies from the range of 18.2-18.8% were obtained for R141b, isopentane and R365mfc. The lowest efficiency, from the range of ca. 17.5—17.9% was obtained in this temperature range of the heat source for R245ca, R124 and acetone.

For a heat source temperature of 100 °C, the highest efficiency of ca. 14.1—14.5 % was obtained for cyclohexane, isohexane, hexane, heptane and methylocyclohexane. Efficiencies from the range of 13.5 to ca. 14.0% were obtained for R123, R245ca, R141b, perfluoropentane, benzene, cyclopentane, isopentane, R365mfc, pentane and R113. The lowest efficiency ca. 13.3 % was obtained in this temperature range of the heat source for acetone.

The results can be used for preliminary selection of the working fluid to the ORC system powered by the flue gases at different temperature levels.

5. SUMMARY AND CONCLUSIONS

The article presents the analysis of the possibilities of using waste heat generated in metallurgical processes to supply ORC systems. The review of waste heat carriers occurring in the iron and aluminum metallurgy processes was carried out. A more detailed analysis was carried out for the copper metallurgy process. On the basis of the conducted analysis, the particularly interesting waste heat resources occurring in the waste gases from the electric furnace and the stationary and rotary anode furnaces were indicated. The enthalpy of these gases could be used to power the ORC system. The calculation model of the ORC system with a regenerator has been proposed. Then, based on thermal parameters of the heat source (i.e., waste gases) and thermodynamic parameters of working factors (i.e., critical parameters and condensing temperature), a number of substances that could be used as working fluids of the ORC system were selected. For these substances, calculations of the ORC system efficiency were made using the model. Modeling results indicated that it is possible to use waste heat generated in the copper metallurgy process to supply ORC systems, and the system efficiency reaches values ranging from ca. 13.3 to 35.4% depending on the temperature of the heat source and used working fluid.

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