Utilization of a Latent Heat Storage for Waste Heat Recovery from an Aluminum Die Casting Plant and the Supply of Preheating and Heat Treatment Furnaces with Stored Heat

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Abstract. Aluminum die casting is an important industrial process and due to melting very energy intensive. Currently, there is a lot of unused waste heat from moulding and cooling in the casting cell. This represents the source of waste heat utilization in this paper. A preheating furnace act as a proper and large enough heat sink. Hence waste heat supply and demand not always coincide a latent thermal energy storage is used to close this gap, utilizing the melting and crystallization enthalpy of the storage medium, the phase change material (PCM). For waste heat recovery and continuous preheating, we designed a system consisting of PCM storage and preheating furnace. At the laboratory at the Austrian Institute of Technology (AIT) there is a PCM storage unit, where experiments can be carried out. As a first step a simulation model was developed using Modelica/Dymola, where thermal oil is used to utilize the waste heat from die casting to preheat aluminum ingots. Simulation results showed that with this system energy savings of 10 to 15% can be achieved and even be surpassed by further optimization. With higher waste heat temperatures (up to 300 °C) and therefor higher preheating temperatures, and an optimally interconnected system of larger PCM storages, energy savings up to 30% seem possible.

Keywords: Aluminum die casting · waste heat recovery · preheating · energy efficiency · simulation · latent heat storage · phase change material

1 Introduction

Energy storage systems can compensate the divergence between fluctuating energy sources (e.g. waste heat, renewables) and discontinuous demand (e.g. batch processes). This enables an increased integration of renewable energies and a strengthening in energy security1].

Besides that, industrial processes face a similar problem, where waste heat supply and demand do not always coincide. Therefor thermal energy storages can be used to match the demands, resulting in increasing overall efficiencies and a reduction in energy

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consumption. Laia Miro et al. investigated various industrial use cases for thermal energy storages in combination with waste heat recovery [2].

Thermal energy storages (TES) can be divided in three major categories. Thermochemical heat storages use the principle of heat due to composition and decomposition of molecules. These storages have high capacities, but a poor controllability. Sensible heat storages are directly proportional to the temperature change and therefor mainly depending on the sensible heat capacity of the storage medium. Latent heat storages are using the enthalpies during a phase transition and therefor capacities are higher compared to sensible storages in most cases. The materials in these storages are called phase change materials (PCM). Due to the isothermal phase change, this type of storage has the advantage of delivering heat at a constant temperature [3].

Metal production and processing in 2019 had a share of 15% of Austria's industrial energy consumption [4] Light metals have advantages in weight, mechanical strength, malleability, corrosion resistance and durability. The most important light metal is aluminum. [5] It is the most produced non-ferrous metal and is increasingly replacing steel components. The production of aluminum is a highly energy intensive process with a corresponding negative environmental effect [6].

Casting as a manufacturing process plays a major role in today's industry. The casting process for aluminum consists of melting, casting, heat treatment and mechanical processing. For the melting process different furnaces are used (crucible, shaft, bath, multi-chamber and rotary melting furnaces) to melt up aluminum ingots and mix alloys [7].

For the forming of aluminum, die casting is the most important casting technology, in which the molten aluminum is formed into intermediate products or end products in a casting process. This process consists of a temperature holding furnace, where the liquid aluminum is stored before casting takes place, the casting machine itself, several temperature control units to balance the energy of the casting tool, a spraying robot to avoid sticking, and a mechanical processing step 8].

When high-performance products are necessary heat treatment processes are conducted to increase hardness and strength of the product. This usually takes place in three steps: solution heat treatment, quenching and aging. The last step of the casting process is a mechanical finishing using turning and milling.

Waste heat recovery from the melting and casting process can reduce energy consumption significantly. [9] This paper focuses on a PCM storage integration into an aluminium die casting process to reuse waste heat from die casting to preheat aluminum ingots.

2 Energy Efficient Foundry – Green Foundry 4.0

The processing of molten metal is very energy intensive. Roughly 25% of die casting product costs are attributable to a form of energy consumption. In the non-ferrous metal industry approximately 60% of the energy used comes from natural gas. The remaining 40% is consumption of electrical energy. [7].

Melting is the main contribution to total energy consumption and counts for roughly 50%. Followed by the casting cell with 25%. The remaining 25% are attributable to postprocessing and compressed air (see Fig. 1). [10].

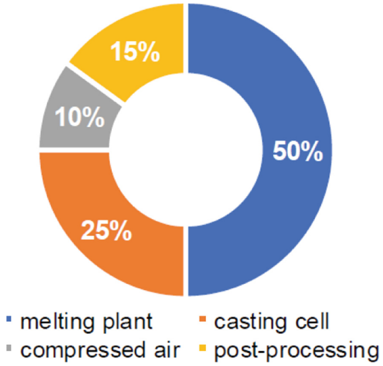

Fig. 1. Energy consumption of a foundry. [10]

There are several possibilities to optimize or adapt the casting process steps to increase energy efficiency and reduce energy consumption. Some research was done on evaluating energy efficiency improvements in the die casting process using cloud computing and an Internet of Things approach. The results showed that with the mentioned approaches 5–10% savings in energy are achievable. [11] [12].

For aluminum having a melting enthalpy of roughly 400 kJ/kg and a melting point in the range of 600 and 700 °C (depending on the composition of the alloy) the energy consumption of a melting furnaces is estimated to be 6–17 GJ per ton, when using natural gas in a crucible furnace. [13] Gas fired crucible furnaces exhibit very low energy efficiencies between 7% and 19%. Internal preheating with flue gases can be achieved with a shaft furnace and can raise the thermal efficiency to 40% to 45%. This principle is described in the BAT document for foundries. The main sources of thermal losses in the melting process are radiation and off-gases. [14].

Beside thermal insulation of furnaces and energy recovery from off-gases, the main goal is the reduction of the energy input. The proposed concept (in line with cited literature) is described in the further course of this paper.

In the casting tool liquid aluminum coming from the melting furnace is formed to products like steering wheels, chassis parts etc. The solidification of aluminum and the cooling of the die casting part to approximately 300 °C needs heat removal, which is still provided by a temperature control unit (thermostat). For waste heat recovery from the individual die casting cells a new central heat distribution system is currently being developed in the project envIoTcast to be set up and tested at the LKR Ranshofen in the course of the Green Demo Foundry. In conventional molding machines heat losses occur through radiation and convection to the environment. Insulating the casting tool properly enables heat extraction with thermal oil from the cooling channels for heat recovery. Utilization of heat from the casting tool is the aim of this paper. [15, 16].

Heat treatment processes mainly take place in large electric or gas heated furnaces. Solution heat treatment (homogenization) takes place between 450 °C and 550 °C while the aging process occurs between approx. 140 °C and 190 °C. As it can be seen in Fig. 2, heat treatment is a potential sink for waste heat from the casting process, resulting in a reduction of (electrical) energy consumption. Inigo Bonilla-Campos et al. investigated

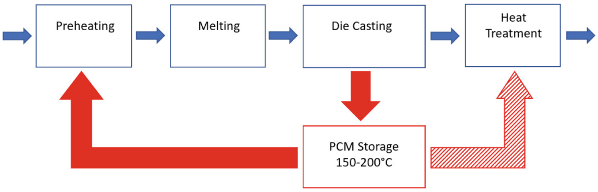

Fig. 2. Process steps of a foundry and possible paths of heat recovery

waste heat recovery in aging furnace as part of the heat treatment, with a potential reduction in energy consumption of the aging furnace by 55%. [9].

Hence not all aluminum die cast parts are undergoing a heat treatment, this process as a sink may not be large enough for all the excess heat to be recovered. In addition, the mass of the die casting parts undergoing a heat treatment is lower, because the sprue resulting from the casting process is removed. This leads to a mismatch between surplus heat and heat demand for heat treatment. For preheating of raw material, the situation is different. Such furnaces have the capability to utilize high amounts of waste heat, because the mass flow of aluminum ingots is large enough to serve as a proper heat sink. This paper focuses on the utilization of waste heat in such a preheating furnace. Figure 2 shows the already described process steps with an additional preheating step.

In general, such a preheating step utilizes waste heat from other process steps to reduce the energy consumption of the melting process. Theoretically, preheating of aluminum ingots from 20 °C to 200 °C reduces the energy consumption of the melting furnace by roughly 16%. Such concepts have hardly been used in the aluminum casting industry to date. It is expected that future foundries will be able to provide heat from the casting process at elevated temperatures of about 300 °C. This preheating temperature could save up to 30% of energy.

3 PCM Storage and Preheating

Since waste heat supply of the casting process and heat demand do not always match, a latent heat storage (PCM) is used to ensure continuous preheating of the raw material.

The aim of this work is to evaluate the feasibility of waste heat recovery via PCM storage and the conceptual design of a suitable preheating furnace.

3.1 PCM Storage

The advantages of a PCM storage system compared to sensible heat storage systems are the higher storage densities and a constant temperature during phase change. [3].

The PCM storage itself is a combination of sensible and latent heat storage. Sensible heat is stored due to a change in temperature of the PCM and the other parts of the storage (e.g. heat exchanger, housing), whereas latent heat results from the enthalpy of the phase change of the storage medium. Organic salt is used as phase change material and thermal oil Marlotherm SH serves as the heat transfer medium. A fin-tube heat exchanger transfers the heat between the thermal oil and the organic salt (see Fig. 3).The principle and design of the PCM storage corresponds to the one described by Zauner et al. [17].

The described PCM storage system was developed and tested in the laboratory of the Austrian Institute of Technology (AIT) in the course of the research project EDC-Sproof. Figure 4 shows the experimental setup of the PCM storage in the lab. The validated PCM storage simulation model from Zauner et al. [17] was used, since it showed good agreement with experimental data and the boundary conditions for this work are comparable.

This paper will investigate the possibilities of charging the storage with waste heat from die casting and utilizing the stored heat.

Fig. 3. Solidified organic salt in the fin-tube heat exchanger of the PCM storage.

Fig. 4. Laboratory test setup of the PCM storage at AIT. Right: Thermostat; Left: Storage with measurement equipment and data logger

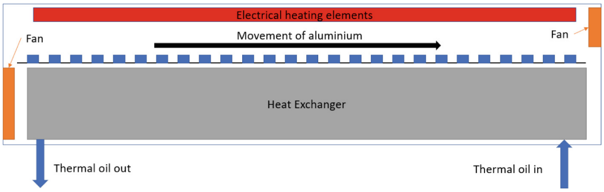

Fig. 5. Conceptual design of a preheating furnace.

3.2 Preheating

As already mentioned, preheating the raw material results in a reduced energy consumption for the melting process.

The company "innoval technology" as part of Danieli Group already provide preheating furnaces, which are gas-fired. They follow the approach of optimizing temperature uniformity within the ingots to reduce heating times. [18] Other preheating studies focus on preheating the ingots with exhaust gas, solar thermal heat or with hot casting products. [19] [20] [21].

A conceptionally designed preheating furnace, as it can be seen in Fig. 5, is used to utilize the stored heat from the PCM storage for a continuous preheating. Inside the furnace aluminum ingots move linearly through the furnace. Heat is provided using thermal oil via a fin-tube heat exchanger at the bottom of the furnace to heat up the air in the furnace. This heat exchanger uses the same thermal oil as the one in the PCM storage. To ensure the heat transfer to the furnace air and to the ingots, there are fans in the furnace to increase turbulence and thus the convective heat transfer. Such a preheating furnace can also be optionally equipped with additional electric heating elements on the furnace ceiling, to use excess electricity if necessary.

The conceptional design of this furnace was modelled and simulated in Modelica/Dymola and will be explained in more detail in the further course of this paper.

4 Storing and Utilization of Waste Heat

Beside the simulation model of the preheating furnace, a simulation model of the system was developed (consisting of furnace and storage) to simulate heat transfer from the storage for preheating the aluminum ingots in the furnace. Another separate simulation model was developed to charge the storage. It shows the feasibility of waste heat utilization by integrating the PCM storage in the casting process and the operation of a preheating furnace with stored heat.

4.1 Storing of Waste Heat

The waste heat from the casting process is transferred to the storage via thermal oil with a supply temperature of 200 °C and a mass flow rate of 0.25 kg/s. The casting process itself is not modelled. For the aim of this paper mass flow rate and supply temperature of the thermal oil are kept constant. A detailed hydraulic scheme is being worked out at

LKR Ranshofen. The validated PCM storage model is discretized with 144 steps, which leads to the necessary accuracy. The phase change temperature of the organic salt is 165 °C and the initial temperature for charging is 155 °C. Due to higher temperatures of the thermal oil, the PCM temperature rises up to the phase change temperature (sensible heat). After complete melting at constant temperature (latent heat) the PCM temperature rises to the final temperature. The goal is to match the energies for storing and utilizing of stored heat, as well as the discharge time for preheating and the charging time through the die casting process.

4.2 Utilization of Waste Heat

The developed simulation model (Modelica/ Dymola) focuses on the utilization of the waste heat stored in the PCM in a continuously operated preheating furnace to reduce the energy consumption of the melting furnace. For this purpose, the model consists of the validated PCM storage sub-model with closed thermal oil circuit connected via heat exchangers to a closed air circuit within the furnace for continuous heating of the aluminum ingots. The ingots move through the furnace in discrete steps, changing position at time intervals. The furnace and thus the heat transfers are divided into 3 zones. Depending on the position of the individual ingot, it receives the heat flux from the respective furnace zone. The closed thermal oil circuit transfers the heat to the air via a fin-tube heat exchanger. The heat transfer was modelled using thermal resistances with heat transfer coefficients and heat transfer areas as input. This heat transfer was also divided into 3 zones to keep the temperature difference of the thermal oil between the zones low. The mass flow of thermal oil in the circuit is kept constant and cools down while in counter-flow heating up the air which itself in counter-flow heats up the ingots. The cooled thermal oil is then returned to the PCM storage inlet. The implemented fan in the model is used to define the direction of the air flow and should ensure the turbulences for proper heat transfer. The structure of the simulation model of the system with the described components is shown in Fig. 6.

At the considered furnace temperatures, radiation is negligible. Additional heat losses through walls or losses due to charging of ingots are also neglected. The present model is generic, what means it can also be used for heat treatment applications and other materials (e.g. steel).

5 Simulation

The developed simulation models were simulated for 5 h to investigate the charging of the PCM storage with waste heat from the die casting process, and the preheating of 250 aluminum ingots with stored heat from the PCM storage. The simulation results below show the proof-of-concept of the proposed waste heat recovery system. Concepts in other foundries may differ.

5.1 Simulation Parameters

This section contains the most important parameters for the simulation. The aluminum ingots have a length of 60 cm and a width of 12 cm. The furnace has a length of

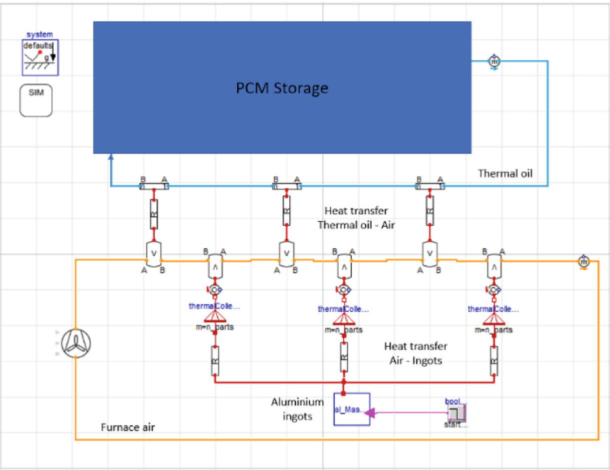

Fig. 6. Dymola model utilizing stored heat for preheating of aluminum ingots

9 m to ensure sufficient heat transfer. The length of the ingots results in a furnace width of 80 cm. The mass flow of the aluminum ingots is 7.5 kg/min, which leads to a conveying velocity of the furnace of 0.2 m/min for a given furnace length. This results in a residence time of 45 min for the ingots inside the furnace. From the Stefan Boltzmann law it follows that the temperature enters the heat flux to the 4^{th} power. Due to the fact that the considered temperatures for this use case are low and below 200 °C, radiation is negligible and the dominant heat transfer is convection. The convective heat transfer coefficients are sufficiently high to ensure a reasonable geometry. They are in the magnitude of about 50 W/m^2K for the convective transfer to the air and of about 250 W/m^2K for the heat transfer of the thermal oil to the tubes of the heat exchanger. Using our versatile simulation model, we can carry out parameter studies to identify the most suitable furnace design for many different applications.

5.2 Results Waste Heat Storage (Charging)

In this section the results of the PCM storage model with constant thermal oil parameters (mass flow and supply temperature) are discussed. Based on the selected parameters, the considered PCM storage has a storage capacity of about 55 to 60 kWh and can be charged in less than 5 h with a maximum capacity of 25 kW (see Fig. 7). The initial temperature of the storage for charging is 155 °C. This is the state of the storage after being discharged and is a result of our system design. When the temperatures of PCM and thermal oil are the same, the storage's state-of-charge is marked as "full".

This is in good agreement with the discharging behaviour, when the stored heat is utilized described in the next section. The modelled storage system has a maximum charging power of approximately 25 kW. As the temperature difference between PCM and thermal oil decreases with increasing state-of-charge also the charging power decreases (see Fig. 8 and Fig. 9).

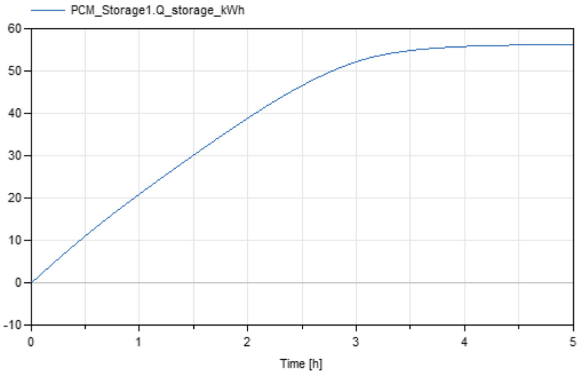

Fig. 7. State-of-charge during charging.

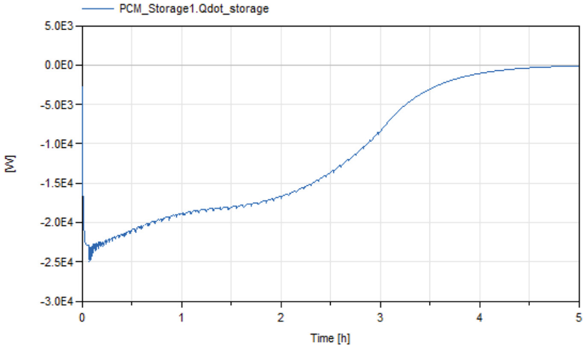

Fig. 8. Thermal power during charging.

Results show that the charging power and the assumed heat flux from waste heat recovery in the casting process can be matched. During the phase change, the charging power remains roughly constant, before it decreases again at complete liquefaction. Figure 9 shows a similar plateau, where the phase change temperature is located at temperatures of 165 °C. The figure shows the temperature of the thermal oil at the outlet of the PCM storage. Results show that the phase change lasts for approximately 1.5 h.

After 5 h inlet and outlet temperatures both approach 200 °C, meaning the storage is fully charged.

5.3 Utilization of Stored Heat (Discharging)

In this section the discharging behaviour of the PCM and the preheating of the aluminum ingots will be discussed. The preheating of the 250 aluminum ingots leads to a discharge of the PCM storage of approximately 55 kWh within 5 h. Compared to the charging behaviour with waste heat from the casting process, where the storage can be charged with 55 to 60 kWh in less than 5 h (see Fig. 7), it shows the possibility of an integration that makes sense in terms of time. This means that the storage can be charged and discharged periodically several times a day making it economical attractive. Theoretically assuming an aluminum foundry with a gas consumption of a gas-fired melting furnace of 30 GWh per year and a gas price of 100 €/MWh and a CO_2 price of 80 €/ton and energy savings of 20% would result in an estimated reduction of costs by roughly 700.000 € per year. The number of storage cycles as well as the savings potential can keep the payback period low.

Due to the recirculation of the thermal oil cooled by the heating of the ingots, the discharge power of the storage remains almost constant over time and delivers the necessary power of 12 kW to heat up the ingots in a continuous way (see Fig. 10).

At the beginning, the power builds up continuously, as the furnace is only gradually filled with ingots. Due to the return of thermal oil to the storage, the phase change area is also extended. After the discharge of sensible heat in the first 2.5 h (see Fig. 12), phase change of the PCM occurs (latent heat extraction) where the ingots can be heated up to almost uniform temperature. A noticeable drop in power occurs only after 4.5 h (see Fig. 11). Figure 12 shows thermal oil temperatures leaving (blue) and re-entering (red) the furnace, and the air temperature (green) in the furnace. The temperature difference between thermal oil inlet and outlet is approximately 30 K, corresponding to the already mentioned almost constant discharging power.

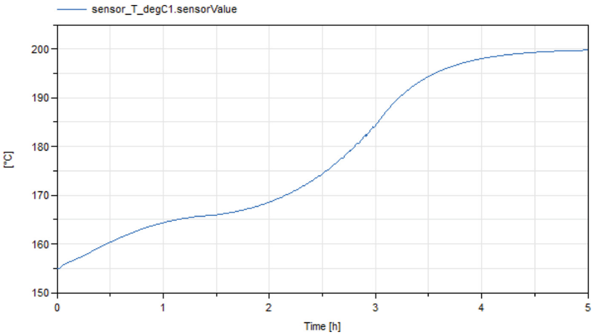

Fig. 9. Temperature of thermal oil at the outlet of the PCM storage during charging.

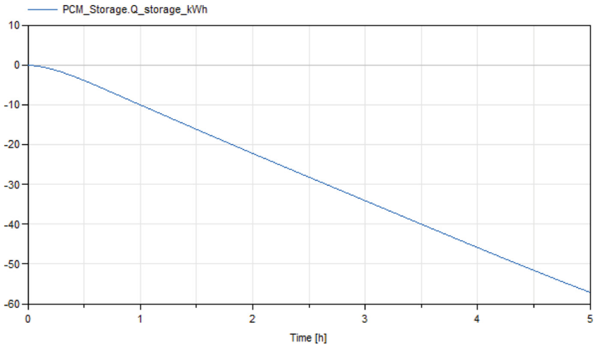

Fig. 10. State-of-charge during discharging.

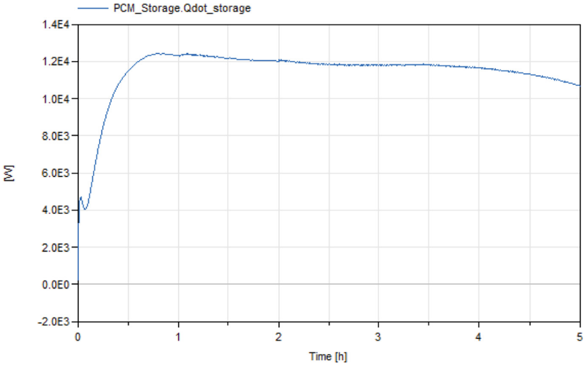

Fig. 11. Thermal power during discharging.

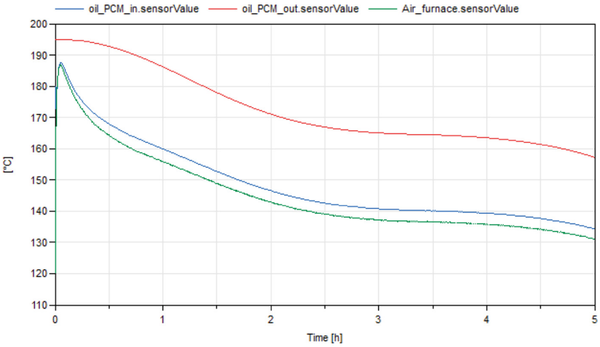

Fig. 12. Temperatures of thermal oil and furnace air.

The temperature difference between the thermal oil at the inlet of the storage (or outlet of the furnace) and the furnace air is approximately 3–5 K. The temperature differences at the beginning are smaller due to the loading of the furnace with ingots. After 45 min the furnace is fully loaded with ingots. The furnace air heats the aluminum ingots and thus also represents the maximum preheating temperature. Overall, the ingots can be heated up to between 160 °C and 130 °C with decreasing temperature over time, as the thermal oil and air temperature in the furnace decreases over time. As already mentioned, the mass flow of thermal oil is kept constant. To further improve the system in the future the mass flow might be controlled to regulate the temperature. This may fix the decreasing temperatures of the ingots. Figure 13 shows the temperature profile of every 50th aluminum ingot when transported through the furnace.

In this simulation setting the ingots stay for 45 min in the furnace. The heating time is influenced by the heat transfer coefficient and duration in the furnace. Preheating of 250 aluminum ingots from 20 °C to the simulated temperatures (see Fig. 13) results in 12% reduction in energy consumption of the melting furnace. The results show a proof-of-concept, however, the system can still be optimized significantly. For example, with the mentioned mass flow control of the thermal oil, but also with larger storage units,

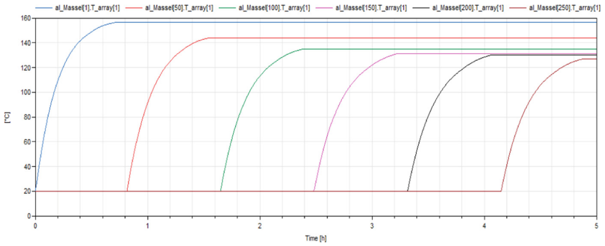

Fig. 13. Temperature profile of every 50th ingot transported through the furnace.

which are interconnected with each other. With further improvements energy savings of up to 30% might be achievable.

6 Conclusion

In die casting processes a lot of unused waste heat exists, due to molding and cooling. A simulation model that utilizes this heat source with thermal oil for preheating of aluminum ingots was presented. Additionally, a PCM storage to match waste heat supply and demand was integrated, to ensure an uninterrupted preheating. The proof-of-concept showed that the proposed waste heat recovery system with a PCM storage can save 10 to 15% energy but can still be further optimized. The model utilizes thermal oil from the die casting process (waste heat from the tool) at 200 °C and heats aluminum ingots up to 160 °C. Future foundries are expected to utilize higher waste heat temperatures of about 300 °C due to an improved casting tool insulation and optimized cooling channels. A first estimation showed that this can result in energy savings of up to 30%. Furthermore, larger storages, optimized interconnection between several storages and auxiliary heating with excess electricity may generate higher and more uniform preheating temperatures.

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