Energy savings during aluminium ingot pre-heating – a modelling approach

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Abstract

Energy consumption of plant is a major contributor to its carbon footprint. As global warming increases in importance, contribution from metal rolling plants must also be addressed. The largest contributors to the energy consumption during the production of aluminium sheet are the metal melting and ingot pre-heating processes. These contribute significantly more than the rolling process itself. Therefore if energy is to be saved, these metal heating processes should be the first ones to be considered. This paper presents an approach to minimising the energy consumed during the pre-heating of aluminium ingots prior to rolling. It is based on a more thorough understanding of the metal temperature distribution during the heating process and of the contributors to energy loss, through mathematical models developed by Innoval. Better evaluation of the metal temperature enables higher initial furnace air temperatures to be used without over-heating any parts of the ingot, allowing shorter cycles to be used, thus reducing heat loss and increasing metal and furnace availability. The approach is to use a mixture of modelling and experimentation. The paper demonstrates the importance of leakage of air into a gas-fired furnace and the benefits which may be obtained by using recuperation.

Keywords: energy, furnaces, aluminium, pre-heating, modelling, leakage, recuperators.

Introduction

Most aluminium ingots which are subject to hot rolling must be homogenised in a pre-heat furnace. The pre-heat furnace also serves to raise the temperature of the metal ready for hot rolling. It requires about 1.1 MJ of energy per kilogram of final product to effect the pre-heating using a conventional pit furnace. This compares with about 0.2 MJ/kg for the hot rolling process itself. Thus if process energy is to be reduced, the pre-heating is one of the first places to look for savings. Pit furnaces for pre-heating are still in wide use by rollers of aluminium flat products. Although they are not the most efficient method of pre-heating, they do provide a flexible store of ingots to maximise availability of metal to the hot line. A key role of the pre-heat facility is to ensure that the hot mills, where the greatest capital is tied up, are kept occupied with production. Figure 1 shows a schematic of a gas-fired pre-heat pit furnace showing also the major sources of energy loss from the furnace.

In order to achieve satisfactory final properties, the temperature distribution in the ingot after the pre-heat must be uniform. For this reason, pre-heat cycle length is sometimes excessive because the actual metal temperature distribution is not known. It is an advantage to know this temperature distribution in the ingot throughout the pre-heating process so that cycle lengths are not prolonged unnecessarily. Shortening cycles is one of the best ways of saving energy per kg rolled, as heat is lost from the furnace even when the ingot is simply being held at temperature. Measuring the temperature distribution during the heating cycle for every ingot is not feasible. This is where a well-calibrated mathematical model of the temperature distribution is of great value in helping to control the process and minimising energy usage.

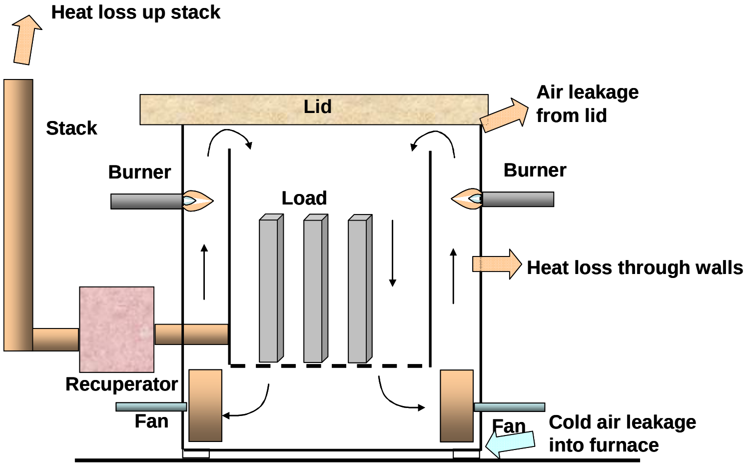

Figure 1 Schematic of a gas-fired pre-heat furnace

Furnace modelling

Innoval Technology have developed such a model to allow the monitoring of the metal temperature at all places in the ingot during the pre-heat cycle. The model also includes the main energy aspects of the cycle.

Figure 2 shows how the ingot is discretised for modelling purposes. The model can accommodate an ingot made up of composite slabs of different alloys. If the ingot or composite is symmetrical, then only a quarter of it is modelled, assuming through-thickness symmetry. If there is not through-thickness symmetry then a half of the ingot is modelled. It is not possible to assume symmetry at the semi-height position as there is a significant air temperature drop down the ingot during the heating process, especially at the start.

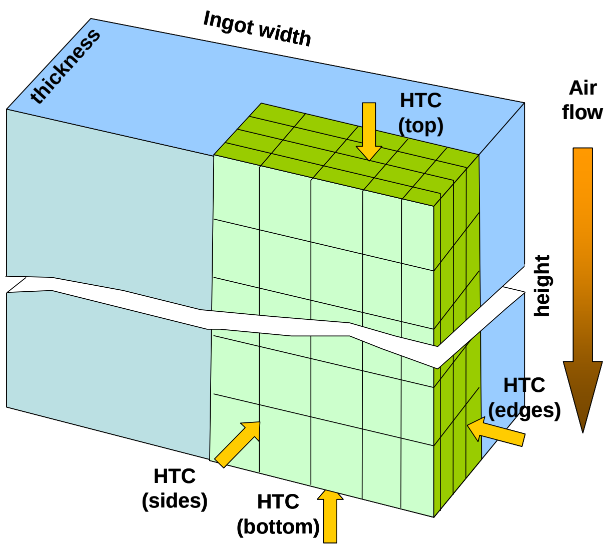

Figure 2 Model of an ingot

The model performs [3D] transient calculations of temperature at the centre of all the elements in the ingot throughout the heating cycle. The boundary conditions for the model are the air temperature and the heat transfer coefficients on the ingot surfaces. These can be determined from first principles and then the model calibrated against experimental data from furnace trials. The model can handle loads of ingots with different sizes. If it is known that ingots in some parts of the furnace are heated differently from others then this can also be handled by running the model for each individual ingot with appropriate calibrations to suit the ingot location.

Figure 3 shows how the air temperature drop down the ingot is typically reflected in the temperature in the ingot itself. This shows the temperature distribution inside an ingot in the vertical plane at the mid-width position for a typical pre-heat process after 5 hours in the furnace. There is about 85℃ difference at this stage between the ends of the ingot.

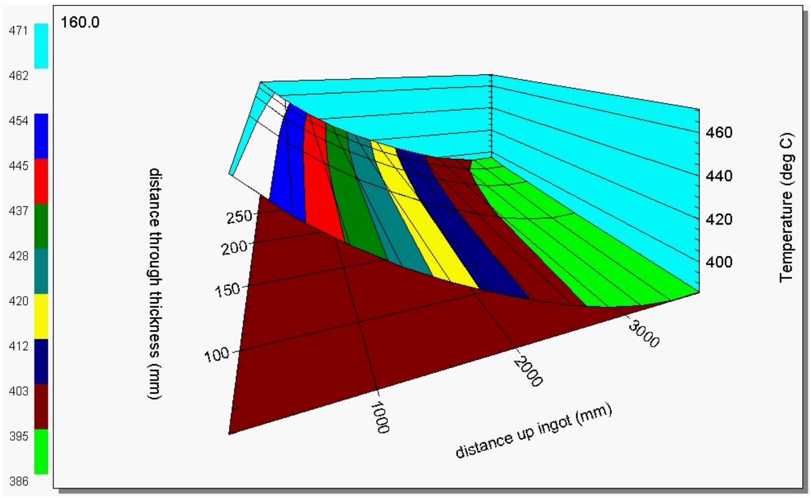

Figure 3 Temperature distribution in an ingot at mid-width position
after 5 hours into the heating cycle

Energy lost through the furnace walls, roof and floor and by re-heating cold air which has leaked into the furnace and replacing hot air which has leaked out must be provided by the burners, thus increasing energy usage. In direct gas-fired furnaces, energy is also lost up the exhaust stack, roughly in proportion to the firing rate, since combustion gas flows must result in an equal flow out of the furnace up the stack. In these cases some of this energy can be recovered by placing a recuperator in the exhaust gas flow to pre-heat the combustion air. All these aspects must be included in the modelling if energy is to be properly considered in the design of the heating cycles.

Using the model to reduce energy

The important temperatures from the point of judging how to improve the cycle are the hottest (leading) and coldest (lagging) anywhere in the ingot through the cycle. Consider a pre-heat schedule in which 12 ingots each of 9.1 tonnes are heated to a target temperature of 600C over a period of 20 hours. Figure 4 shows the leading and lagging temperatures through the heat-up time for a typical pit furnace. All parts of the ingot must have a temperature between these two curves. In order to achieve the required properties, the temperature throughout the ingot must reach the required value and this can easily be assessed with a calibrated model. Figure 4 shows a fixed value for the set air temperature. It may be noted from Figure 4 that the ingot temperature becomes essentially uniform after 14 hours.

Figure 4 also shows the energy losses during the cycle. In this case it has been assumed that a recuperator is in place. It is typical for about twice as much energy to be supplied to the furnace as is required to raise the temperature of the metal. In the cycle shown in Figure 4, the energy added to the ingots is about 65GJ whereas that supplied during the 20 hours is 110GJ. A significant amount of energy (about 12GJ) is added after the ingots have reached the required temperature due to stack and wall losses during the "hold" part of the cycle.

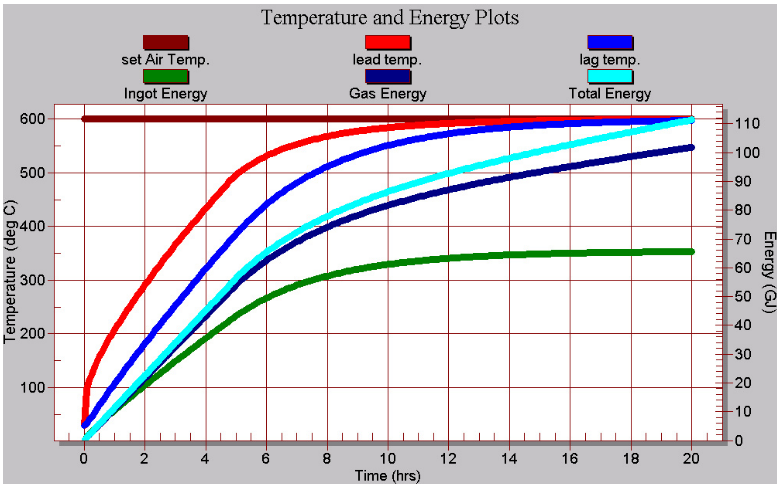

Figure 4 Ingot leading and lagging temperature and energy consumed during a typical pre-heat cycle with constant set-air temperature

Shortening heat-up times

It is possible to accelerate the early part of the cycle by using higher set air temperatures. Figure 5 shows significantly higher than target air temperatures used at the beginning of the heat-up. The model indicates that for the time they are used there is no danger of over-heating any part of the ingot. Because the model effectively can give warning of excess temperature anywhere on the ingot it allows a more aggressive heating regime which can enable a reduction in overall heating time without danger of damaging the ingot. This shows that the ingots become available for rolling 2 hours earlier and consume 4GJ less energy. This represents a 4% energy saving.

This technique pre-supposes that there is sufficient power in the burners to maintain the air temperature at or near its set value. It is important to include the power limits in the modelling and thus model the actual air temperature, not just the set value. The problem of power limitation is most acute at the start of the cycle when the ingots and furnace structure can absorb heat at a high rate because the are relatively cold. Maintaining the correct set air temperature is also more of an issue in indirectly fired furnaces where there is no direct contact between the combustion products and the re-circulating air.

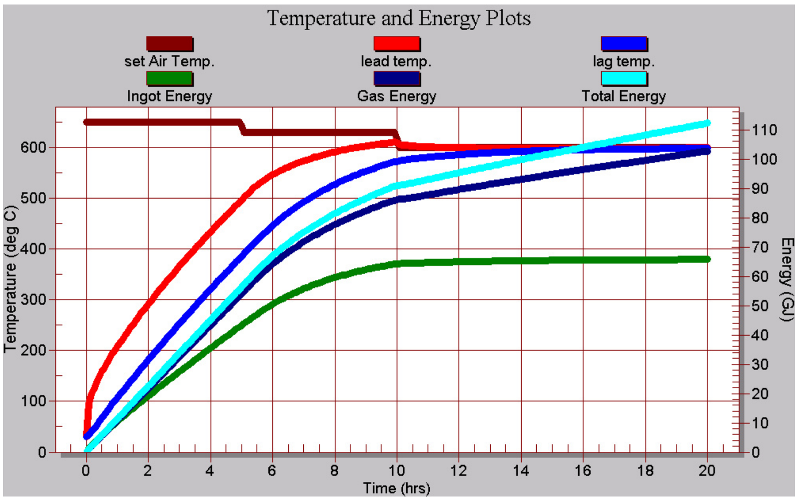

Figure 5 Ingot leading and lagging temperature and energy consumed during a typical pre-heat cycle with higher initial set-air temperature

Recuperation

In a direct fired gas furnace, a mass of air corresponding to the combustion gas and air must be extracted from the furnace and exhausted up the stack. This represents a significant energy loss. However, it can be considerably reduced by the use of a recuperator which recovers heat from the exhaust stream and transfers it to the incoming combustion air. A recuperator is a heat exchanger often consisting of a tube stack enclosed in a shell or box. The hot exhaust air passes through the recuperator tubes and the incoming combustion air is drawn over the external surfaces of the tube stack. The air is thus heated on its route to the burners. Figure 6 shows the level of benefit which may be obtained by using a recuperator with a surface area of 100m2. This indicates a 12% reduction in the total energy supplied, or 16GJ, which amounts to a saving of about 0.15MJ per kg of pre-heat load. This level of saving usually means that a recuperator will pay for itself in about 12 months at present energy costs. As energy becomes more expensive and as the drive to reduce carbon emissions increases, recuperators will become more and more attractive. Sometimes the recuperators are fitted to the burners themselves. These are known as recuperative burners. They are generally smaller and cheaper but less efficient than stand-alone recuperators.

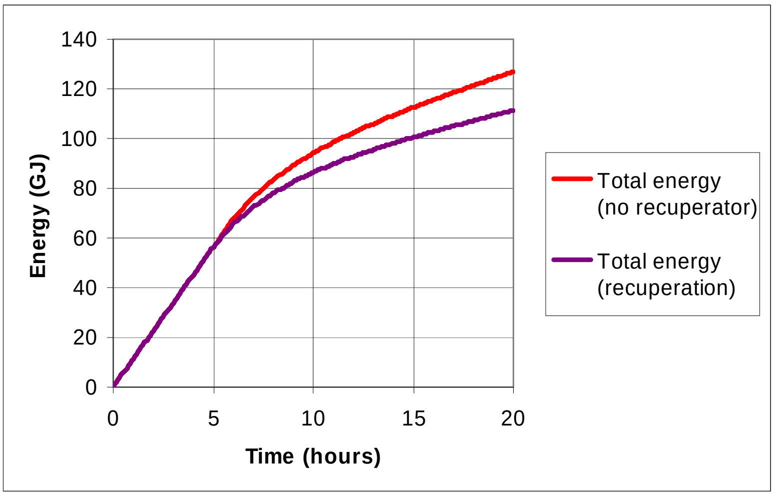

Figure 6 Effect of a recuperator on energy consumption

Air leakage

Another contribution to the energy lost from furnaces is due to air leakage out of or into a furnace. If no recuperator is fitted, it is possible to tolerate quite large leakages of air out of the furnace without affecting the energy efficiency. This rather surprising fact is because the combustion air must be extracted up the stack and air leaking out of the furnace simply reduces the flow up the stack by the same amount. Clearly, however, if the air leakage exceeds the combustion air requirement then there will be significant energy loss. This can more easily occur towards the end of the cycle when the gas firing level is low. Furthermore, if a recuperator is fitted, even low levels of air leakage out of the furnace are important as the recuperator can only recover heat from air which passes through it.

Usually there are parts of the furnace which operate below the ambient static air pressure. This is often near the base of the furnace close to the re-circulating fan intake. If the furnace is not well sealed in this region, cold air can be pulled into the furnace from outside. This has a more serious affect than air leaking out, as the in-coming cold air must be heated up to the operating temperature of the furnace.

Figure 7 shows the effect of a leakage of 0.2 m3/s of air into the furnace. This level of air leakage has been measured on a pit furnace in use. When air leaks in, the energy loss over the 20 hour period is about 11GJ or an increase in energy of 9%. This is a significant increase in the energy supplied. Leakages of air into a furnace are not so obvious to the operators as there are no visible effects as occurs with air leaking out.

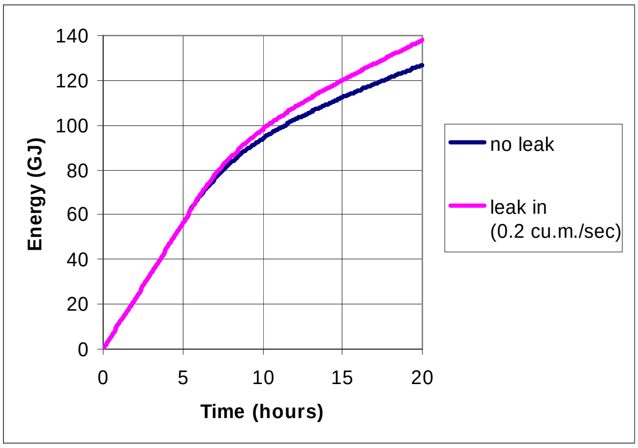

Figure 7 Effect on energy consumption of air leaking into a furnace

Summary

A modelling approach, developed by Innoval, can yield practical pointers to shortening ingot pre-heat times by enabling more aggressive heat-up schemes to be used without danger of over-heating the ingot. It also indicates ways of significantly reducing the energy losses of the process. Models are being used more and more as part of the process control and it is possible to envisage that in the near future these furnace models will be running on-line, calculating the best future settings for the furnace and providing warnings of furnace malfunction much earlier than would otherwise be recognised. Innoval has experience of developing and applying models to help clients explore the potential energy savings in both Aluminium pre-heating and steel re-heating processes.