Reducing Fuel Consumption in Soaking Pit

—Inverted-L Type Heating Practice*

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Synopsis

Conventional practice of heating steel ingots in soaking pit consists in setting the pit temperature at about 1300°C upon charging hot steel ingots into the soaking pit, feeding the fuel at a maximum flow rate at the early period of heating, and gradually reducing the flow rate of the fuel when the pit temperature has reached the set value. When the steel ingots heated for a definite period of time have reached the uniform temperature throughout, the soaking process is completed and they are extracted and rolled. For this reason, large quantities of heat are given off as the sensible heat of exhaust gas and as heat radiation from the pit. This situation is not desirable for saving energy. To cope with this high fuel price age after the oil shock, the authors have studied heating methods and developed "the inverted-L type heating practice", a new method entirely different from conventional heating methods. This method consists in heating steel ingots with the fuel at a minimum flow rate required for heat balance until the latent heat of solidification has spread throughout the steel ingots, increasing the fuel flow rate just before extraction, and thereby abruptly heating the surface. The average unit fuel consumption decreased from 183×10^3 kcal/t in 1973 to 111×10^3 kcal/t in 1977 when this method was adopted, thus showing a decrease of 34%.

1. Introduction

Soaking pits in the slabbing and blooming mills of Fukuyama Works, Nippon Kokan K.K. (NKK), had an average fuel consumption of 183×10^3 kcal/t in 1973. Because of the high fuel costs after the oil crisis, NKK has initiated various fuel consumption reduction programs in its Nos. 1 and 2 slabbing and blooming mills by improving the combustion process, operation, and equipment. A further program was pushed forward in the No. 3 mill (used as a model mill), for which construction was completed in November, 1973, for the purpose of improving the heating pattern. The main object consisted of positive exploitation of the potential heat of steel ingots, and, as a new heating pattern, the Inverted-L Type Heating Practice was developed. This practice has decreased the fuel consumption of the No. 3 mill from 119×10^3 kcal/t (1974) to 69×10^3 kcal/t (1977), which is an outstanding reduction of as much as 42%. The fuel consumption of the slabbing and blooming mill as a whole, has been reduced by 34% from 169×10^3 kcal/t in 1974 to 111×10^3 kcal/t in 1977.

In this paper, the results are reported on the reduction of soaking pit fuel consumption in the slabbing and blooming mills of the NKK Fukuyama Works attained by employment of the inverted-L type heating practice.

II. Operation on Soaking Pits

1. Characteristics of Top One-way Fired Soaking Pits

Of various types of soaking pit, the top one-way fired type is used in some 73% of the pits in Japan.¹⁾ This is attributable to its compact construction as well as excellent applicability to a large-capacity pit. Also related to this popularity is the industrial application of high speed burners using high-velocity air, which was impossible in the case of the conventional tile recuperator and was made possible only after the adoption of the metallic recuperator currently showing rapid progress.

Notwithstanding these advantages, this type of pit has its own drawbacks. Under the structural conditions inherent to this type, the combustion gas flow becomes uni-directional and takes the form of a horizontal "U". Accordingly, excessive temperature difference occurs within the pit: for example, a temperature difference of as much as 50° to 120°C is easily caused between the point opposite to the burner (hot point) and the point near the exhaust gas port below the burner (cold point).^{2,3)} To remove this problem, various improvements have been made on the burner and other combustion systems, including principally the method to accelerate agitation of the pit atmosphere by giving spinning motion to the combustion air and fuel and the use of variable flame burner with which the burner flame length is controlled in each heating stage. Though these improvements have successfully decreased temperature difference, no observable reduction was found in fuel consumption.

2. Various Approaches to Reduce Fuel Consumption

In principle, four approaches can be considered: (1) Increase the potential heat of the steel ingot to be charged into the soaking pit; (2) Reduce the potential heat of steel ingot to be discharged from the soaking pit; (3) Improve the thermal efficiency of the soaking pit; and (4) Reduce the heat loss of the pit during idle times. In addition to these, heat by scale formation also exerts great influence. Since the scale is reused as an iron source, we will not go deeply into this subject, but will concentrate our discussion on the above four approaches.

Approach (1): Increasing the potential heat of charged ingot

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Charged steel ingots are mostly hot, and retain unsolidified portions. Figure 1 shows the ingot thermal history after casting.⁵⁾ Ingot temperature transition varies depending upon the time from casting to charging into the soaking pit (the time referred to as "track time"). In other words, fuel consumption required for heating changes greatly according to the track time. Figure 2 shows the relationship between the track time and fuel consumption at NKK.

This relationship can be expressed by a regression analysis as follows:

$$Q = 30 \times 10^3 \cdot T_t + \alpha \dots \dots \dots (1)$$

where, Q : Fuel consumption (kcal/t)
 T_t : Track time (h)
 α : Constant (kcal/t)

This indicates that the fuel consumption increases by approximately 30×10^3 kcal/t for each one-hour extension of track time, i.e., shortened track time is indispensable for the reduction of fuel consumption. In practice, however, physical conditions of ingot discharging and transportation, and the requirements for the internal qualities of the ingot prohibit extremely short track time. Besides, overly shortened track time causes delay in complete solidification inside the ingot, resulting in undesirably prolonged

Fig. 1. Relationship between ingot temperature and time from casting (by ordinary heating practice)

Fig. 2. Relationship between fuel consumption and track time

pit time.⁵⁾ Therefore, an optimized minimum track time, generally referred to as a reference track time, is determined according to the kind of steel and ingot size, and normal operation control is carried out thereafter on the basis of this reference.

Approach (2): Reducing the potential heat of discharged ingot

This approach is divided into two methods. The first method attempts to reduce heat loss of discharged ingots by resetting the temperature to a lower level or by shortening the pit time. Note here that this method is frequently accompanied by an increase in surface defects, non-uniform elongation during rolling, or cracks. The second method consists of the prevention of unnecessarily prolonged pit time or of heating at extremely high temperature. Overheating, which causes "burning" or accelerates scaling, must be avoided by strictly resuming the ingot discharge schedule. In exceptional cases such as unexpected accidents, etc., it becomes necessary to prevent fuel consumption increase by resetting the pit temperature to a lower level or by cutting off the fuel supply. Figure 3 shows the relationship between fuel consumption and pit time at NKK. Evidently, the fuel consumption rises by approximately 10×10^3 kcal/t for each one-hour extension of pit time.

Approach (3): Improving the thermal efficiency of soaking pit

It is essential here to establish how effectively the heat produced from burning the fuel can be utilized for heating. To ensure effective utilization, heat loss in exhaust gas and furnace body radiation must be reduced by keeping combustion at the optimum air-fuel ratio,⁶⁾ shortening the period to retain high pit temperature, and increasing the heat recovery by a recuperator.⁷⁾ In the case of soaking pit, the fuel and air flow rate changes from the maximum flow rate by several percent. Thus, instrumentation has to cope with very unstable operating conditions and can supply, only with the greatest of difficulty, combustion air at the proper air-fuel ratio. In many cases, automatic control of oxygen content in the exhaust gas is employed to prevent excess air supply.⁸⁾ Finally, in view of excessive difference in exhaust gas temperature and preheated air temperature from one heating method to another, heating pattern improvement is also essential.

Approach (4): Reducing the heat loss of uncharged pit

Fig. 3. Relationship between fuel consumption and pit time

Unless an adequate amount of fuel is burnt during idle pit-times, the pit temperature drops substantially, and hence an extremely large amount of fuel and long heating time will be required prior to starting the subsequent heat. Evidently, the reasonable way to keep the uncharged pit in optimum condition is to be sought for. Fundamentally, a short idle time should be aimed at by determining the adequate number of operating pits to catch up the production, ensuring proper pits operation, and by establishing a well thought out tapping schedule.

3. Theoretical Analysis of Heating

Figure 4 shows the heating cycle from the ingot charging up to a point where the rolling temperature is reached. Fuel consumption during this cycle (area of shadowed section in the figure) is the fuel consumed in heating ingots. This fuel consumption differs greatly depending upon the potential ingot heat, heated tonnage, set temperature, and idle pit-time before charging. By limiting our observation to the fuel consumption during heating, namely, the fuel consumption from charging to discharging the authors find that this remains substantially constant if the kind of ingot, track time, and heating method are the same. This means that a fuel consumption data analysis by computer can pinpoint principal affecting factors. This analysis makes clear critically that track time variation due to different kinds of steel affects fuel consumption. At NKK Works, this consumption is 80×10^3 kcal/t for capped steel, 120×10^3 kcal/t for semi-killed steel, 160×10^3 kcal/t for killed steel (excl. high tension steel), and 300×10^3 kcal/t for high tension steel. Based on this information, fuel consumption is estimated by using the following formula:

$$y = A \cdot a + B \cdot b + C \cdot c + D \cdot d \dots\dots\dots(2)$$

- where, $a+b+c+d=1$
 y : Target fuel consumption (kcal/t)
 A : Standard fuel consumption of capped steel (kcal/t)
 B : Standard fuel consumption of semi-killed steel (kcal/t)
 C : Standard fuel consumption of killed steel (excl. high-tension steel) (kcal/t)
 D : Standard fuel consumption of high-tension steel (kcal/t)
 a : Capped steel ratio
 b : Semi-killed steel ratio
 c : Killed steel ratio (excl. high-tension steel)
 d : High-tension steel ratio

This simple polynomal expression helps setting the daily and monthly fuel consumptions for the difference in component steel kinds, and thus will prove useful in daily operation control. Furthermore, by introducing such elements as lag or extension of track time into this expression, control with better accuracy can be achieved.⁹⁾

Apart from the aforementioned indispensable control, the thermal history of ingot internal temperature from ingot casting to the end of heating in the soaking

pit, if fully understood, will also help determine reasonable heating practice. Determination of above said thermal history by actual measurement, however, is difficult, so that estimation by calculation has been attempted instead.

To determine this thermal history the unsteady state heat conduction formula below is solved for a specified initial condition. The ingot's thermal history is determined by solving the difference analogue of Formula (3).¹⁰⁾

$$c \rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) \dots\dots\dots(3)$$

- where, T : Temperature ($^{\circ}\text{C}$)
 c : Specific heat (kcal/kg $\cdot^{\circ}\text{C}$)
 ρ : Density (kg/m³)
 k : Heat conductivity (kcal/m $\cdot\text{h}\cdot^{\circ}\text{C}$)
 x, y : Coordinates(m)
 t : Time (h)

As values for physical properties change against temperature, Formula (3) is rewritten into a linear formula by using the following conversion scale:

$$\phi = \int_{Td}^T \frac{k}{kd} dT \dots\dots\dots(4)$$

$$\partial H / \partial T = C \dots\dots\dots(5)$$

Namely, from above Formulas (4) and (5), Formula (3) is turned into the following formula:

$$\frac{\partial H}{\partial t} = \frac{kd}{\rho} \left(\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} \right) \dots\dots\dots(6)$$

- where, kd : Thermal conductivity at an arbitrary base temperature (kcal/m $\cdot\text{h}\cdot^{\circ}\text{C}$)
 Td : An arbitrary base temperature ($^{\circ}\text{C}$)
 H : Total heat content per unit weight (kcal/kg)

Heat transmission by radiation and convection under the boundary conditions is as follows in each heating and cooling process:

Initial condition: $T_{is} = T_0 - 1\ 550^{\circ}\text{C}$ at $t = 0$
 $T_m = 150^{\circ}\text{C}$
 $T_b = 30^{\circ}\text{C}$

- Boundary conditions:
(1) Heat transmission by radiation and convection between the mold outside surface and atmosphere (from pouring to stripping)

$$q = \sigma \cdot \varepsilon_m \{ (T_{ms} + 273.2)^4 - (T_b + 273.2)^4 \} + \alpha (T_{ms} - T_b)$$

- (2) Heat transmission by radiation between the mold inside surface and ingot surface (from the air gap formation)

$$-q = \sigma \cdot \varepsilon_i \cdot \varepsilon_m \{ (T_{is} + 273.2)^4 - (T_{ms} + 273.2)^4 \}$$

- (3) Heat transmission by radiation between the ingot surface and mold inside surface (from the air gap formation to stripping)

$$q = \sigma \cdot \varepsilon_i \cdot \varepsilon_m \{ (T_{ms} + 273.2)^4 - (T_{is} + 273.2)^4 \}$$

Fig. 4. Pit cycle in heating ingots by ordinary heating practice

Fig. 5. Comparison of rapid heating practice and ordinary heating practice

Fig. 6. Fuel flow rate and temperature in two-step heating practice

(4) Heat transmission by radiation and convection between the ingot surface and atmosphere (from stripping to charging into pit)

$$q = \sigma \cdot \varepsilon_i \{ (T_{is} + 273.2)^4 - (T_b + 273.2)^4 \} + \alpha (T_{is} - T_b)$$

(5) Heat transmission by radiation and convection of ingot surface in the pit (after charging into pit)

$$q = \sigma \cdot \varepsilon_i \{ (T_f + 273.2)^4 - (T_{is} + 273.2)^4 \} + \alpha (T_f - T_{is})$$

where, q : Heat flux ($\text{kcal/m}^2 \cdot \text{h}$)

$\varepsilon_m, \varepsilon_i$: Emissivity of mold and ingot

σ : Stephan-Boltzman constant ($\text{kcal/m}^2 \cdot \text{h} \cdot \text{K}^4$)

T_m, T_{is} : Surface temperatures of mold and ingot ($^{\circ}\text{C}$)

T_f : Pit atmosphere temperature ($^{\circ}\text{C}$)

T_b : Ambient temperature ($^{\circ}\text{C}$)

α : Heat transfer coefficient by convection ($\text{kcal/m}^2 \cdot \text{h} \cdot ^{\circ}\text{C}$)

T_0 : Casting temperature ($^{\circ}\text{C}$)

According to this calculation method, various heating methods are analyzed theoretically.

4. Conventional Heating Practices

1. Ordinary Heating Practice

In conventional heating practice, the charged ingot is heated by combusting the fuel and air on the burner, with the set pit temperature fixed at around 1300°C . During the initial stage, fuel flow reaches a maximum level, and decreases gradually when the set pit temperature is reached. After the ingot is soaked by heating for a predetermined period, it is discharged from the pit and rolled. This practice is called ordinary heating practice, and has been employed widely because of simple pit control and high heating ability. Figure 4 shows the transition of pit temperature and fuel flow rate in this practice. If higher productivity is required, rapid heating practice is employed, in which an initial set temperature which is higher by 20° to 30°C is selected. Figure 5 shows the comparison between this practice and the ordinary heating practice in terms of pit temperature transition and fuel flow rate. However, the thermal conductivity of the ingot is determined from the thermal diffusion rate inside the ingot, which is different from thin slab. When the heated ingot surface reaches a temperature nearly equal to the set pit temperature,

heat transmission thereafter is restricted to the heat diffused from the surface inward. Accordingly, it is necessary in the above practices to keep the pit at high temperature while the heat diffuses into the center of the ingot. As a result, most of the combustion heat is lost as sensible heat in exhaust gas, deteriorating the thermal efficiency and raising the fuel consumption.

2. Special Heating Practice

(1) Heating with Controlled Heat Input

Conventional soaking pits are designed to have high maximum heat input because the heating productivity is the prime concern. This means that the fuel consumption is high. In general, optimum heat input appropriate for reducing the fuel consumption is estimated at 60% to 80% of maximum input heat. Accordingly, by controlling the maximum input heat and, corresponding to this, by reducing the size of the exhaust gas port and combustion-air port, fuel consumption can be reduced by 10% as compared with ordinary heating practice.

(2) Two-step Heating Practice

This is an outgrowth of the above described practice. As is evident from Fig. 6, this practice permits the further reduction in fuel consumption of around 10% by selecting the optimum primary set temperature.

(3) Gradient Heating Practice

This practice has a long history of application particularly in the heating of high-tension steel and alloy steel. These kinds of steel frequently crack in the heating. In this practice, the steel ingot is heated at a predetermined temperature gradient ($^{\circ}\text{C/h}$) to control the heating speed and to minimize temperature difference between the inside and outside of the ingot, thereby preventing excessive internal stress. The heating pattern is shown in Fig. 7. This practice uses a special temperature setting device (normally referred to as a program setting device), which performs automatic control of fuel flow to ensure heating at a predetermined gradient. In general, heating speed for high-grade steel is set at 30° to 100°C/h . By selecting any appropriate temperature gradient from 80° to 200°C/h , capped steel and semi-killed steel hot ingot can be heated optimally, enabling 15% reduction in fuel consumption.

(4) Double-gradient Heating Practice

In the gradient heating, an overly gentle tempera-

Fig. 7. Fuel flow rate and temperature in gradient heating practice

Fig. 8. Fuel flow rate and temperature in double-gradient heating practice

Fig. 9. Temperature from discharging for 20 t ingot

ture gradient will result in an ingot surface temperature which is higher than the pit temperature at the initial stage of heating, thereby releasing the ingot potential heat. With an extremely steep gradient, on the other hand, the pit temperature rises too high and increases heat loss in the exhaust gas. During the final stage of heating, when the difference between ingot temperature and pit temperature is lessened, heat input into the ingot slows down. To overcome these problem factors, this practice consists of changing the heating speed halfway during the heating process, instead of heating at the temperature gradient throughout up to the point where the set temperature is reached. Figure 8 shows the heating pattern.

In close cooperation with an instrument manufacturer, NKK has developed a program setting device to perform double-gradient heating, and has applied the device to some pits. If the optimum temperature gradient is set, reasonable heating can be ensured for every type of steel ingot, achieving a reduction in fuel consumption of 15% to 20% compared to that of ordinary heating practice.

Needless to say, the above-described heating practices, though enabling consumption reduction, cannot be applied to a pit without a program setting device. Besides, the setting should be modified depending upon the ingot potential heat. Accordingly, a simpler heating practice is required for the capped and semi-killed steel ingot whose pit time is limited.

III. Inverted-L Type Heating Practice

1. Development of New Heating Practice

If the potential heat of the charged ingot is above the level required for rolling, the ingot will be ready for rolling if kept in perfect insulated condition and by obtaining uniform internal temperature distribution. Generally, capped steel and semi-killed steel are charged into the soaking pit before the ingot inside solidifies completely. Therefore, if the ingot potential heat including the latent heat of the un-solidified portion is maintained above the value required to keep the rolling temperature, the above concept can be applied as it is.¹¹⁾ To roll the ingot heated and discharged from the pit, it is necessary to (1) keep the temperature at every part of the ingot above the level required to enable rolling at optimum rolling force and (2) maintain the surface temperature

sufficiently high to avoid surface defects caused by low temperature during rolling.

In the conventional practices, stress was placed on the high rolling efficiency and discussion was directed to how quickly and uniformly the ingot is to be heated. In practice, most of the effort was concentrated to heat the entire ingot uniformly and thoroughly to its center at the sufficiently high surface temperature required for rolling. This resulted in longer soaking pit time and higher fuel consumption. Considering, however, that rolled slabs, blooms, etc., are normally allowed to cool without further treatment, diffusing its high internal heat wastefully, it is not necessary to heat the inside of the ingot to such high temperature. On the other hand, 3 to 4 min elapse normally from ingot discharging to rolling. During this period, the ingot's corner temperature drops rapidly as shown in Fig. 9. In spite of measures taken to further shorten the required time (for transportation, weighing, etc.) until rolling as well as to enhance the removal of roll cooling water and to increase the rolling speed, this surface temperature drop is unavoidable. It is desirable, therefore, to preheat the ingot surface to a temperature slightly higher than that of the center.

Diagrammatic representation in Fig. 10 shows the temperature distribution of an ingot at charging, which is obtained by solving the unsteady state heat conduction formula. With the rolling temperature at 1 250°C, temperature distribution as shown by an alternate long and short dash line may be considered the lowest allowable in view of the potential heat at ingot discharging. As for the ingot heated by ordinary heating practice, temperature distribution as shown in Fig. 11 is calculated. If the heating is limited to the minimum required, heat corresponding to the dotted section of the figure can be saved.

From these diagrammatic representations, it is evident that effective utilization of ingot potential heat for heating of the surface is most essential to achieve ideal heating with minimum fuel consumption.

Based on the concept so far described, the temperature transition of the ingot having a temperature distribution as shown in Fig. 10 was calculated. Said ingot was left standing in a perfect adiabatic condition. The calculated result is shown in Fig. 12, in which points (1), (2) and (3) in the inset figure will finally reach the same temperature. Here, by keeping

20 t ingot; Track time: 2 h 30 min

Fig. 10. Calculated internal temperature distribution at charging into soaking pit

20 t ingot

Track time: 2 h 30 min; Pit time: 3 h 30 min

Fig. 11. Internal temperature distribution at discharging in an ordinary heating practice

20 t ingot

Track time: 3 h 00 min

Fig. 12. Calculated temperature of ingot after charging under the perfectly insulated condition

Fig. 13. Temperature and fuel flow rate under the nearly insulated condition

the pit temperature on the temperature level at point (2) where the temperature is the highest on the surface, heat radiation from the ingot surface is suppressed and the pit temperature can be kept at the minimum required level. Figure 13 shows the calculated fuel input to obtain the temperature at point (2). The figure is related to the central cross section of the ingot. In actual operation, the pit temperature becomes somewhat lower for the same fuel flow, as shown by a dotted curve in Fig. 13, because of the effect exerted by the low temperature ingot top and bottom. Notwithstanding that, the tendency remains

the same.

The ingot surface thus obtains approximately uniform temperature. To carry out extra heating of this ingot to compensate for the temperature drop expected until rolling, fuel is allowed to flow in a high-flow rate for a very limited period immediately before the ingot discharging. Temperature distribution on the ingot surface at discharging is as indicated by the solid line of Graph (1) in Fig. 14 for high fuel input and by the broken line for low fuel input. Temperature distribution at rolling is shown for both cases in Graph (2). In the case of temperature distribution indicated by the broken line, the surface temperature becomes too low, causing surface defects. Therefore, it is necessary to increase the heat input. In this way, the heat input required to accelerate surface heating, namely, "Fuel flow rate $\times$ Input

Fig. 14. Diagrammatic representation of ingot surface temperature

Fig. 15. The ideal heating practice

time", was determined from factory tests.

On the basis of synthetic analysis of these concepts, the model pattern of ideal heating, as shown in Fig. 15, was determined. Long pit-time leads to the necessity of keeping the pit at a high temperature for a long time, resulting in heat loss by heat radiation from the furnace body or in exhaust gas. Accordingly, this high-temperature period must be minimized. In view of this, we have set the target pit-time; namely the shortest period which can satisfy the requirements such as (1) the temperature difference within the range permitting rolling, (2) completely solidified ingot inside at discharging (required from quality aspect), (3) surface temperature at discharging above a level necessary for rolling. In other words, target pit-time is the time needed to allow the ingot inside to solidify completely. Switching to high fuel flow is made slightly before reaching the pit time. However, ingot discharged according to this pit time schedule does not always have uniform temperature distribution, and some portion thereof may remain below the rolling temperature range. In addition, the potential heat varies among ingots, and the top and bottom portions of the ingot have insufficient potential heat. To overcome these problem factors, the authors have determined the inverted-L type fuel input pattern by inputting extra fuel empirically. t_1 , t_2 , q_1 , and q_2 were determined to have optimum values adequate for the ingot potential heat or operating conditions.

Fig. 16. Internal temperature distribution at discharging in an inverted "L" heating practice

Fig. 17. The inverted "L" heating pattern

Figure 16 shows the temperature distribution of an ingot heated by the inverted-L type heating practice, which was determined by the aforementioned calculating method. As is evident from the figure, temperature distribution, though not completely flat, becomes substantially level as compared with the ordinary heating practice.

2. Application Example and Effect of Inverted-L Type Heating Practice

Figure 17 shows the example of application of the inverted-L type heating practice to the capped steel. When twelve 15 t ingots are charged, the fuel consumption is 46×10^3 kcal/t, which is 35 to 40% reduction as compared with ordinary heating practice. To put this practice into practical application, the set value of low fuel flow and the pit temperature at switching from low to high fuel flow are of particular importance. In actual operation, this practice can provide a proper heating pattern for the ingot whose charging is delayed because of failure to charge within

the reference track-time or for a killed steel ingot whose inside has solidified completely at charging. In these cases, more effective heating can be expected by the three-step constant fuel flow heating, in which the medium-fuel flow period is set between the low and high fuel flow periods.

Figure 18 shows the comparison between the inverted-L type heating and ordinary heating in terms of heated ingot quality and rolling characteristics. The surface quality of a rolled ingot was evaluated quantitatively by calculating the percentage of the surface portion which must be conditioned to remove defects. From Fig. 18, it is evident that the evaluated result differs between the inverted-L type practice and ordinary heating practice. Comparison of the power consumption required in rolling shows that the power consumption in the inverted-L heating practice is higher by approximately 1.0 kWh/t. On the other hand, scale loss in the soaking pit, which is closely correlated to pit-time, is lower by approximately 0.1% in the inverted-L type practice, as shown in Fig. 19. These results may easily be explained by the calculated result showing that the average temperature of an ingot heated by the inverted-L type practice

is lower by approximately 30° to 60°C. In addition, the high pit temperature period is short, reducing the scaling on the ingot surface in the soaking pit. This also is considered to cause a slight difference in our evaluation on the slab surface.

Figure 20 shows the change with time of the pit temperature, exhaust gas temperature (at inlet and outlet of recuperator), and preheated air temperature in the inverted-L type heating and ordinary heating practice. In ordinary heating practice, a large quantity of air required in the heating stage, which needs a lot of combustion gas at low pit temperature, causes a temperature drop of the preheated air subject to heat exchange in the recuperator, deteriorating the thermal efficiency. At the soaking stage, on the other hand, little combustion gas is needed at high pit temperature, and hence the exhaust gas temperature becomes high while the air required is reduced. In this case, to protect the metallic recuperator, dilution air is to be added. Though the exhaust gas temperature can thus be lowered, heat recovery efficiency deteriorates. In inverted-L type heating, little air is required at low exhaust gas temperature because of low fuel flow, as high temperature preheated air is obtained. At high pit temperature, high air flow is needed, resulting in the slightly low temperature of the preheated air. Thus, no dilution air is necessary and effective heat recovery is ensured. Finally secondary effects as listed in Table 1 are obtained by the inverted-L type heating practice. Firstly, this practice consists of constant flow heating. Accordingly, the air-fuel ratio is easy to set, and proper oxygen content control of exhaust gas is possible without using the automatic control unit. Secondly, low fuel flow heating is used at the initial stage of the heating. This ensures uniform temperature distribution within the pit. Besides, its slow heating process enables

Fig. 18. Influence of fuel consumption on slab conditioning and electric power consumption

Fig. 19. Influence of pit time scale loss

Fig. 20. Comparison of temperature in an ordinary heating practice and in an inverted “L” heating practice

Table 1. Characteristics of the inverted "L" heating pattern

Features	Advantage
1. Constant fuel flow rate heating	→ Single air/fuel ratio setting
2. Low fuel flow rate at the early stage of heating	→ Uniform distribution of furnace temperature → Reduction of fuel consumption at prolonged pit time → Earlier solidification
3. Short period of high temperature heating	→ Decrease of sensible heat of exhaust gas → Decrease of heat absorbed by furnace body and radiated from furnace surface → Prolongation of life of furnace body → Decrease of scale loss

Fig. 21. Solidification time at a cross-section of 17.5 t ingot

relatively flat temperature distribution within the ingot and small internal stress during heating. In short, this practice can be applied to thermal cracking. In comparison with ordinary heating practice, this inverted-L heating practice produces lower average pit temperature, accelerating the solidification to enable complete solidification within a minimum period. According to the calculation, 15 to 18 t ingots charged in 80% solidified condition will complete solidification approximately 10 to 20 min earlier. As described later, the track time can thus be shortened without affecting the internal quality. Thirdly, the pit is maintained at high temperature only for a limited time period. This enables extreme reduction of heat loss in the exhaust gas and due to radiation from the furnace body, enhancing the thermal efficiency. This also prevents scaling on the ingot surface, and the increase in yield by reducing the scale loss amounts to approximately 0.1%.

3. Reduction of Track Time in the Inverted-L Type Heating

As is evident from the calculation on heat transmission, employment of the inverted-L type heating pattern in a soaking pit ensures that the solidification process is not affected by the shorter track time. Figure 21 shows the change of solidification with time in the thickness direction of an 18 t ingot. Even with

the same track time of 2 h and 40 min, the ingot heated by this method completes solidification 9 min earlier than in the case of ordinary heating.

Here the necessity to regulate the time from casting to complete solidification is ignored. As shown in Fig. 21, the ingot was charged at shortened track time and the point at which the ingot solidifies within about 275 min is determined. Track time of 2 h and 30 min is obtained, which is about 10 min shorter than in the case of ordinary heating practice. Except for a certain portion which solidifies slightly quicker than normal, the core portion solidified at a normal rate. No difference is observed in the product quality. Following this basic concept, track time was shortened for capped steel in August, 1977. By shortening the track time by 10 min, the ingot potential heat can be effectively utilized, and about 5×10^3 kcal/t in fuel consumption is reduced.

4. Heat Balance

To clearly determine the effect and characteristics of inverted-L type heating practice, the heat balance was calculated for both ordinary and inverted-L type heating practices on the basis of the following conditions:

Technical data for heat balance

- (1) Pit under consideration: No. 5 pit (heavy oil burning) in No. 3 slabbing and blooming mill
 - (2) Scope of equipment: Up to the down-take section of pit
 - (3) Operating conditions at measurement: Pit temperature before charging is kept at 1 200°C. Ingots to be charged are of 18 t capped steel, and nine ingots are charged. Track time: 2.5 h
- The calculated heat balance is shown in Table 2. This indicates the following points on inverted-L type heating practice.
- (1) Fuel consumption:
Ordinary heating practice— 74.3×10^3 kcal/t
Inverted-L type — 49.7×10^3 kcal/t
Reduction by —33%
 - (2) Exhaust gas latent heat:
Ordinary heating practice— 43.4×10^3 kcal/t
Inverted-L type — 22.5×10^3 kcal/t
Reduction by —48%
 - (3) Thermal efficiency:
Ordinary practice—34.3%
Inverted-L type —43.5%
Improved by —9.2%

As is evident from above, inverted-L type heating practice has achieved noticeable reduction of fuel consumption through improvement of thermal efficiency.

5. Actual Reduction of Fuel Consumption

As a result of various improvement with emphasis placed on heating pattern, fuel consumption of soaking pits of slabbing and blooming mills in Fukuyama Works have been reduced step by step. Figure 22 shows the transition of total fuel consumption (a weighted average) of Nos. 1 to 3 slabbing and bloom-

Table 2. Heat balance

Ordinary heating practice			Heat efficiency $\frac{33.1}{96.6} \times 100 = 34.3\%$		
Heat input			Heat output		
Item	$\times 10^3$ kcal/t	%	Item	$\times 10^3$ kcal/t	%
(1) Heat by fuel combustion	74.3	76.9	(6) Heat absorbed by ingot	33.1	34.3
(2) Sensible heat of fuel	0.3	0.3	(7) Sensible heat in scale	2.3	2.4
(3) Sensible heat of hot air	10.4	10.8	(8) Sensible heat lost in exhaust gas	43.4	44.9
(4) Heat of atomizer	3.1	3.2	(9) Heat radiated from furnace body	8.3	8.6
(5) Heat by scale formation	8.5	8.8	(10) Heat absorbed by furnace body	9.5	9.8
Total	96.6	100.0	Total	96.6	100.0

Inverted "L" heating practice			Heat efficiency $\frac{29.2}{67.2} \times 100 = 43.5\%$		
Heat input			Heat output		
Item	$\times 10^3$ kcal/t	%	Item	$\times 10^3$ kcal/t	%
(1) Heat by fuel combustion	49.7	74.0	(6) Heat absorbed by ingot	29.2	43.4
(2) Sensible heat of fuel	0.2	0.3	(7) Sensible heat in scale	1.7	2.5
(3) Sensible heat of hot air	7.5	11.2	(8) Sensible heat lost in exhaust gas	22.5	33.5
(4) Heat of atomizer	2.1	3.1	(9) Heat radiated from furnace body	5.5	8.2
(5) Heat by scale formation	7.7	11.4	(10) Heat absorbed by furnace body	8.3	12.4
Total	67.2	100.0	Total	67.2	100.0

Fig. 22. Fuel consumption per ton of ingots at slabbing and blooming mills in Fukuyama Works

ing mills and the fuel consumption in No. 3 slabbing and blooming mill.

Of the three mills in this Works, No. 3 mill, the plant exclusively for the slab for the hot strip mills, has achieved the lowest fuel consumption owing to a substantial reduction in the consumption made since March, 1976. For example, the mill achieved an annual average consumption of 76×10^3 kcal/t in 1976 and 69×10^3 kcal/t in 1977. The monthly average was 58×10^3 kcal/t in March, 1977.

IV. Conclusion

An inverted-L type heating practice has been developed as a heating practice for the soaking pit. Differing from the conventional method requiring long soaking time, this practice is based on a com-

pletely unique concept, and ensures simple operation and high efficiency in reducing the fuel consumption. This practice is also advantageous in various respects. It has been applied to the slabbing and blooming mill of this Works with successful results, and its application can be extended further to general reheating furnaces. In future, a total energy saving program will be developed dealing with direct rolling or hot slab charging. Further promoted will be energy saving in the slabbing and blooming process through effective utilization of exhaust gas latent heat and of radiant heat from slabs and blooms.

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