Development of a Slab Cooling Boiler for Energy Saving and Utilization in Steel Works*

By Yoshiaki SHINOHARA,** Akito TAKAHASHI** and Norihisa SHIRAISHI**

I. Foreward

As-rolled slabs have mean temperature of 1000°C even after shearing, holding a sensible heat amounting to some 160×10^3 kcal/t. Conventionally, this heat was left unused, as the slabs were cooled to room temperature either by water quenching in the rotary cooler, or water spray and air cooling on the cooling bed. A slab cooling boiler (SCB) was developed to recover the sensible heat of hot slabs as steam (16 kg/cm^2 gauge) by way of radiative heat from the slab surface, and to utilize it effectively in the steel works with added benefits of a continuous cooling process and labor saving as well as an increased rotary cooler capacity.

Research and development work was started in 1970, including basic experiments on heat transfer, basic design of the whole facility, and detail design. With the construction commenced in 1974, the facility was placed in operation in March 1976 at No. 2 Slabbing Mill of Mizushima Works of Kawasaki Steel Corporation as the world's first of its kind. The operation in the subsequent years has been smooth with the generation of steam at a rate of 15,000 to 20,000 t/month, providing its efficiency as general purpose steam for heavy oil heating, pipe heating, oil atomizing, pickling line heating, processing in chemical by-product plants, and room heating.

The SCB plant is capable of recovering a heat of 65,000 to 75,000 kcal per ton of slab, an amount equal to or more than the heat consumption of soaking pits for rimmed and semi-killed steels. This report describes the basic experiment on heat transfer, basic design, and outline of the plant and the results of operation.

II. Basic Experiment on Heat Transfer

1. Purpose of the Experiment

In the heat recovery of as-rolled hot slabs, two types of heat transfer are considered: the radiative heat transfer from the slab surface and the conductive heat transfer due to the contact with the water-cooled skid. To estimate the radiative heat transfer, an overall radiant heat transfer coefficient including emissivity and angle factors need to be known. The heat transfer by way of contacting is considered to be worth an active utilization, and an accurate estimation of the heat flux at the contact zone between skid and slab becomes necessary. An accurate knowledge of these heat transfer characteristics is essential in selecting the heat transfer method for heat recovery and in obtaining the slab cooling rate and the heat recovery rate from slab. For the purpose of obtaining the accurate knowledge, an experimental apparatus was manufactured in a capacity large enough for the charging of one actual slab for the basic experiment on heat transfer.

2. Apparatus and Method of Experiment

The experimental apparatus is equipped with water-cooled piping and designed so that the upper part measures the radiative heat from the slab surface and the lower part measures the heat due to the contact with water-cooled skid. The apparatus is thermally insulated from the surroundings, and the amount of transferred heat was obtainable from the amount of water and the temperature difference. Figure 1 shows a schematic drawing of the experimental apparatus, and Fig. 2 the cross-section of the skid.

Experiments were conducted in two separates cases; one was the direct charging of hot slab after slabbing and the other was the heating of a cold slab in the reheating furnace before charging into the experimental apparatus. In the former case, main emphasis was placed on obtaining the amount of radiative heat transferred from the actual slab surface.

In this case, the slab surface temperature was measured by attaching sheathed thermo-couples. In the latter case, main purpose was to grasp detailed heat transfer characteristics with thermo-couples attached to necessary places, especially, the heat transfer due to the contact with skid, the slab cooling rate, and the difference of measured temperature between the method using a thermo-couple welded on the slab surface and the method using a thermo-couple attached on the slab.

The transferred heat due to the contact varies according to the contact pressure (kg/m^2) between slab and skid, which was varied by changing the number of skids that supported the slab. Photograph 1 the slab prepared for temperature measurement.

3. Results of the Experiment

1. Radiative Heat Transferred from Slab Surface

Figure 3 shows the relationships between the slab surface temperature and the radiated heat. Since the surface temperature of an as-rolled slab was measured by the attached thermo-couple, the measurement


** Mizushima Works, Kawasaki Steel Corporation, Kawasaki-dori, Kurashiki 712.
Transactions ISIJ, Vol. 20, 1980

Heat insulating material
Upper heating surface (25A pipes)

Fig. 2. Cross-section of skid.

Fig. 1. Cross-section of experimental apparatus.

The heat flux of radiation is measured by attaching sheathed thermo-couples and measured by welded thermo-couples.

Fig. 3. Relation between the slab surface temperature and the heat flux by radiation.

From Fig. 3, it is found that in obtaining the radiated heat from the slab surface to the water-cooled upper heating surface, it suffices to assume $\phi_{CG}$ to be 0.8 to 1.0 in the radiative heat transfer formula of Stefan-Boltzmann:

$$Q = 4.88 \cdot \phi_{CG} \cdot \left[ \left( \frac{t_s + 273}{100} \right)^4 - \left( \frac{t_0 + 273}{100} \right)^4 \right] \quad ...(1)$$

where, $\phi_{CG}$: an overall radiant transfer coefficient
$t_s$: slab surface temperature (°C)
$t_0$: water-cooled upper heating surface temperature (°C)

It means that the emissivity of steel slab is nearly 0.95. It is also found that $\phi_{CG}$ becomes close to 0.8 when the slab surface temperature is 600°C or higher.

Technical Features
2. Heat Transfer by Contact with Skid

Figure 5 shows the effect of the contact pressure on the heat transfer coefficient for the heat flux from the bottom surface of slab to skid rail. The heat transfer coefficient was calculated from the following formula.

\[
h = \left( q_i - q_o \right) / A + 4.88 \cdot \phi_{CG} \times \left[ \left( \frac{t_s + 273}{100} \right)^4 - \left( \frac{t_r + 273}{100} \right)^4 \right] (t_s - t_r) \ldots (2)
\]

where, \( h \): heat transfer coefficient by contact with skid (kcal/m²h°C)
\( q_o \): amount of heat transferred by non-contact with skid (kcal/h)
\( A \): area of slab surface contacting the skid rail (m²)
\( \phi_{CG} \): overall radiant heat transfer coefficient (assumed to be 0.8)
\( t_s \): surface temperature of slab contacting the skid rail (°C)
\( t_r \): surface temperature of the skid rail contacting slab (°C)

The heat transfer coefficient becomes greater as the contact pressure is increased, but the coefficient depends on the manner of contact even under the same contact pressure; therefore, contact pressure is not the sole factor to determine the coefficient value. Slabs for test Nos. 1 to 4 were as-rolled and therefore they were expected to have thicker edges after the final pass. This is why the slab surface does not make a uniform contact with skids, exerting unpredictable contact pressures.

In test Nos. 5 to 12, both edges of slab were cut by 200 mm and an effort was made to make the slab surface flat so as to attain a uniform contact with skids. In this case, the heat transfer coefficient is more closely related with the contact pressure, and is 3.5 times the upper surface radiant heat at a contact pressure of 39,900 kg/m².

Assuming the contact pressure is 40,000 kg/m² and roughness of slab surface (height of peak) is 0.1 mm, the heat transfer coefficient by contact is about 310 kcal/m²h°C from the well known equation of heat transfer coefficient by contact. This value nearly equals those of test No. 12.

3. Slab Cooling Rate

Figure 6 shows the cooling curve of 190 mm thick test slab measured at a portion free from the effect of skids. It also shows a calculation of one-dimensional heat transfer equation by the finite difference method regarding the same portion. Also, in this calculation, \( \phi_{CG} = 0.8 \), the ambient temperature = 40°C and the specific heat, thermal conductivity and density of 0.06% C rimmed steel were used for estimating the radiated heat from the slab surface. For slab temper-
temperatures of 500°C and higher, good correspondence is seen between measurements and calculations.

4. Temperature Distribution of the Skid-contact Zone

Temperature distribution of the skid-contact zone of a 190 mm thick slab was calculated using the two-dimensional heat transfer equation by the finite difference method. In this calculation, the heat transfer coefficient between skid rail and slab was taken to be 180 kcal/m²h°C, conforming to the experimental result; water temperature, 40°C within skid pipe; convection heat transfer coefficient of water, 2000 kcal/m²h°C; specific heat, thermal conductivity and density of skid those of the 0.08%C killed steel. Other factors were assumed to be the same as in the case cited above.

Figure 7 shows measured and calculated temperature distributions after 15 min. from the charging into the experimental apparatus. Calculations are not always in perfect agreement with measurements, but the factual state of heat transfer due to contact is fairly well indicated. The temperature gradient in the thickness direction in the skid-contact portion of the slab is 12°C/mm, and that in the non-skid contact zone (upper surface of slab) is 1.7°C/mm, indicating that better contact gives rise to faster cooling rate.

III. Basic Design of SCB

1. Heat Transfer Method of SCB

Basic experiments on the heat transfer showed that the heat transfer due to contact with skids can be 3.5 times the radiated heat transfer, when the contact is good. Generally it is difficult to attain such a good contact over the entire surface of the skid. Especially, in an as-rolled slab both edges of which are expected to be considerably thick at the final pass, a uniform contact becomes more difficult.

In the case of a partial improvement for contact, the temperature distribution within the slab is fairly ununiform as shown in Fig. 7, bringing the temperature gradient down to 12°C/mm at the contact zone. It is conceivable that this will lead to the problems of cracking and warping. Furthermore, in using the skid pipe for boiler tubes, a 200×10⁶ kcal/m²h heat flux is transferred to boiler tubes when in good contact, calling for a special countermeasure as boiler tubes.

For the reasons mentioned above, a conclusion was reached that it would be better to use only the radiative heat transfer for the heat transfer. Hence, it was decided to use dry skids for both walking and stationary beams for the slab transfer equipment, thereby avoiding the effect of heat transfer due to contact.

2. Length of SCB

As a prerequisite for the length of SCB, it was decided that the length must be economical in view of the heat recovery and the equipment cost, and that the temperature of conventional slab for air and/or water spray cooling must be reduced below the transformation point at the entry to a rotary cooler.

Figures 8 and 9 show the results of calculations of slab cooling curves after discharging an ingot from the soaking pit, slabbing, entering SCB for further cooling. Figure 8 shows the surface temperature of slab and Fig. 9 shows the center temperature. The ambient temperature was assumed to be 200°C, and other calculation conditions and the specific heat, thermal conductivity and density used in the calculation were the same as in II. 3.3.

From the cooling curves of slab, the heat loss of slab within SCB can be calculated, and it can be recovered as steam. By using this theory, relations between the length of SCB and the amount of steam generation were obtained by simulation model using the slab of No. 2 Slabbing Mill. The results are shown in Fig. 10. Case 1 shows the calculation for an average slab handling of 412 t/h at No. 2 Slabbing Mill based on 12 million t/y raw steel capacity at Mizushima Works. Case 2 shows the calculation for 252 t/h of average slab handling when the works has an annual 8 million ton capacity. These calculations show that 50 to 60 m may be the best for SCB, and especially in case 2, 60 m or longer is not necessary. Also, the length of SCB as mentioned above will give a 2.5 h holding time in SCB to the conventional slab for air and/or water-spray cooling, considering the amount of rolling. It follows therefore that the slab surface temperature at the rotary cooler entrance will

The heat transfer coefficient between a skid rail and a slab was assumed to be 180 kcal/m²h°C.

Fig. 7. Calculated and measured temperature distributions of a slab riding on skid pipes (15 min after slab charging).
be 700°C or lower, based on Figs. 8 and 9. For this reason the length of SCB was determined to be 54 m. Figure 11 shows relations between the slab charge rate and the steam generation rate for fixed SCB length of 54 m. Based on the preceding calculations, it was
decided to design the steam generation from SCB to be 40 t/h (average) and 70 t/h (max.) in consideration of efficiency.

3. Layout of SCB Plant

Figure 12 shows the layout of the SCB plant at No. 2 Slabbing Mill. Since SCB has a pre-cooling facility in which after a part of senside heat of hot slab is recovered and the slab is cooled, the slab is sent to the rotary cooler for water quenching to room temperature. Therefore, the SCB was installed by passing the rolling line, divided into two sections for turning back. No. 1 and No. 2 SCB’s are both 27 m long and 13 m wide. This layout permits a continuous rolling operation at the time of troubles with SCB or at the time of inspection by governmental authorities. Furthermore, not only the commercial grade slabs but also slabs that have been cooled by air and/or water-spray at the cooling bed can be handled continuously. In addition, charging and discharging of slabs into SCB and their transport to the rotary cooler are all performed automatically.

4. Steam Transport System

Steam generated from SCB is sent to the central portion of the steam main pipe extending 8 km from the south to the north of Mizushima Works, and used for the general purpose (16 kg/cm² gauge) in the steel works. The steam generation system treats the steam bred from the fuel combustion boiler, the BOF waste heat recovery boiler, the steam turbine, the back pressure turbine, de-pressure and de-superheat of high-pressure steam (88 kg/cm² gauge) and the SCB.

Major applications of steam are heavy oil heating, pipe heating, oil atomizing, pickling line heating, processing in chemical by-product plant, degassing in steel refining, lubricant heating, room heating and bath. The steam quantity, in both demand and supply, varies from time to time. For a long-range variation, the demand and supply balance is met by controlling the steam quantity from the steam turbine and back-pressure turbine and the number of combustion boilers for operation. For short-range variation, the balance is met by the fuel combustion boiler. In the fuel combustion boiler, the pressure of the steam main pipe is controlled by the fuel consumption rate; therefore, when steam generation from SCB is large, the consumption of fuel decreases. In other words, heat recovery in SCB results in fuel saving.

IV. Outline of SCB Plant

1. Slab Specification

No. 2 Slabbing Mill processes two types of slab; one for hot strip and the other for plate, both in a variety of dimensions. Slabs chargeable to SCB have the specification shown in Table 1, and slabs of any other dimensions and slabs of alloy steel specified for slow cooling in the holding furnace can not be charged. At present, the rate of chargeable slabs is 90%.

2. Structure of SCB

Figure 13 is a schematic drawing of SCB. SCB is 27 m long as one unit, composed of upper boiler tubes, lower boiler tubes, and a walking beam for

![Fig. 12. Layout of the SCB plant and slab flow.](image-url)
conveying slabs. The upper boiler tubes is 13 m wide, 1.2 m apart from the lower boiler tubes. The upper boiler tubes consist of 10 units which are U-shaped in the length direction of SCB.

Photograph 2 shows a unit of the upper boiler tubes. The lower boiler tubes are aligned in checker form with 90 mm space in two rows (top and bottom) between stationary and walking beams. The alignment prevents the piling of scale from slabs. Photograph 3 shows the lower boiler tubes and walking beams. There are 8 rows of walking beams in the width direction and 16 rows of stationary beams. Driving system is of hydro-pressure inclination rail type.

3. Boiler Equipment

SCB is of forced circulation type, and water is supplied by the circulation pump from the steam drum to the upper and lower boiler tubes of No. 1 and 2 SCB. The recirculation boiler water containing steam because of the heat absorption at each boiler tube is separated into water and steam when returning to steam drum, with only the steam carried to the steam main pipe.

Table 2 shows main specifications of the boiler equipment. Though SCB can not be furnished with such a safety device as a fuel stopper in the fuel combustion boiler in the case of power failure, SCB is equipped with 2 units of steam driven recirculation pumps and 1 unit of a water supply pump. A steam drum, a recirculation pump, a water supply pump

<table>
<thead>
<tr>
<th>Table 2. Boiler specification.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steam pressure</strong></td>
</tr>
<tr>
<td>Evaporation</td>
</tr>
<tr>
<td>Heating surface (total)</td>
</tr>
<tr>
<td>Boiler water circulating pumps</td>
</tr>
<tr>
<td>Numbers required</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Boiler feed water pumps</td>
</tr>
<tr>
<td>Numbers required</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Steam drum</td>
</tr>
</tbody>
</table>

Technical Features
and a deaerator are installed in the outside of the boiler station. Photograph 4 shows the boiler station.

V. Operation Results

Since its start in March 1976 as the world's first of its kind, SCB has been in smooth operation. Photo. 5 shows a general view of SCB as seen from the slab entry side of No. 1 SCB.

1. Slab Charging Rate and Steam Generation Rate

The evaporation rate depends upon the charging conditions, i.e., dimensions, type of steel, weight and slab charging rate. Figure 14 shows relationships between the slab charging rate and the evaporation rate. The maximum evaporation rate is 70 t/h as originally planned.

Figure 15 shows relationships between the slab charging rate, the evaporation rate and the steam generating coefficient. Here, the steam generating coefficient is defined as the weight of evaporation (t) per a ton of charged slab.

The steam generating coefficient is largely affected by the time for a slab to stay in SCB. In Fig. 15, the dotted line shows the original planning of the steam generating coefficient, which becomes smaller as the charging rate becomes larger. In comparing actual values with the planned values, the former exceeds the latter when the slab charging rate is large, and falls below the latter when the slab charging rate is small. This means that when hot slabs are retained in SCB, the heat recovery efficiency becomes higher than the planned value.

For 0.10 t-steam/t-slab of the steam generating coefficient, a heat of 72 000 kcal is required, assuming the steam is obtained from the fuel combustion boiler. In other words, the heat energy equivalent to 72 000 kcal/t-slab is recovered. This is equal to or more than the heat consumption of rimmed steel and semi-killed steel in soaking pits.

2. Monthly Rate Steam Generation

Figure 16 shows the monthly rate of steam generation from March 1976 till December 1977. The monthly average of the evaporation rate was 16 300 t/month, and the total was 342 000 t.

Fuel saved in this process is 28 000 kl as Minas heavy oil. In addition, a 60% saving was attained for the marine water consumption in the rotary cooler,
contribute to the reduction in the warm water discharge and to the saving in electric power. Furthermore, the passage of slabs through SCB instead of quenching at the rotary cooler contributes largely to improving the shape of slab, easy slab handling in the subsequent processes mending.

**VI. Conclusions**

Developed jointly by Kawasaki Steel Corporation and Kawasaki Heavy Industries, SCB was installed at No. 2 Slabbing Mill of Mizushima Works, which has a 12 million t/y raw steel capacity. The development was aimed for effective utilization of part of the sensible heat of as-rolled hot slabs by way of radiative heat transfer, continuous slab cooling, labor saving, and increasing the rotary cooler capacity.

Basic experiments on heat transfer at an early stage of the development revealed that an overall radiant heat transfer coefficient of the as-rolled slab surface $\phi_{ca}$ is 0.8 and that the heat transferred by skid contact reaches 3.5 times the radiated heat, amounting to $200 \times 10^3$ kcal/m$^2$h for the contact pressure of 39 900 kg/m$^2$.

In view of the technical difficulty in obtaining a good contact of slabs with the skid surface; however, it was decided to use only the radiant heat transfer. Other decisive factors were the cracking and warping of slabs, and the high-temperature load on boiler tubes.

A total of 342 000 t steam generated from the SCB plant as of December 1977 since its start in March 1976 is equivalent to a 28 000 kl saving as Minas heavy oil. The heat recovery in this SCB is 72 000 kcal/t-slab. It is equal to or greater than the heat consumption of rimmed and semi-killed steels in the soaking pit.

The SCB technology as an effective utilization of radiative heat transfer from solids is considered to be useful for recovering untapped energy sources still existing in many other forms of high-temperature solids in steel works.

**Acknowledgements**

Last but not least, the authors gratefully acknowledge patient and helpful cooperation extended by many people at Boiler Design Dept., Steel Machinery Dept., and other related departments of Kawasaki Heavy Industries, Ltd. since 1971.