KAWASAKI STEEL TECHNICAL REPORT
No.7 (March 1983)

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Synopsis :
A cold spot temperature control system for the batch annealing furnace has been established in order to reduce energy consumption, to imporove productivity and to stabilize the properties of products. This system is called the "Coil Annealing Prediction System (CAPS)." Through the use of the exact heat transfer model, the CAPS can predict the necessary lowest temperature of each coil in the furnace for producing the coil having the suitable mechanical properties, and stop heating the coils, when the temperature of the coldest point reaches the predicted value. Since its practical use in May 1980, CAPS has been operating smoothly and achieved more than 10% energy cost saving.

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1 Introduction

In recent years, energy saving has been actively pursued in various fields of the iron and steel industry. In the cold rolled strip manufacturing process, the energy used in the annealing line accounts for approximately 50% of the overall consumption. The reduction of the per product ton energy consumption during annealing (including fuel, electric power and atmospheric gas) is one of the most important problems in the cold rolling plant.

For this purpose, a number of energy-saving measures, such as the use of convector plate for improving heat transfer, and the installation of a recuperator, have been adopted. Of course, cutting the annealing time would be most effective in reducing the energy consumption per ton product during annealing. The annealing process, however, plays an important role in recrystalizing the microstructure distorted by rolling and ensuring product quality of adequate workability. Hence, it is impossible to reduce the heating time without limits. This situation is attributed to the failure in measuring the temperature of the coil during annealing. The Coil Annealing Prediction System (CAPS)[1-2] developed by Kawasaki Steel Corporation allows accurate estimation of the temperature at its cold spot (about 1/3 of coil's radius from outer side) of the stacked coils by using the coil annealing finish prediction formula derived from a heat transfer simulation model[3]. The estimate thus obtained tells when to end the heating when the cold spot temperature reaches the target level required for realizing the specified mechanical properties.

This report concerns the heat transfer simulation serving as the basis of coil annealing finish prediction, the coil annealing finish prediction model and the effects of applying CAPS to actual furnace operation.

2 Description of Annealing Furnace

In the batch tight coil annealing furnace, which is one of the cold rolled strip annealing methods[4], the heat is transferred to the coil mainly through convection from the atmospheric gas which flows through the convector plates arranged between coils as shown in **Fig. 1**. However, as coils are stacked, it is hardly possible to keep such items constant as the temperature and flow speed of atmospheric gas around stacked coils on base stools, and to heat and cool stacked coils uniformly. Moreover, the temperature sensors for monitoring the phenomena in the annealing furnace provide only the temperature at the edge of the lowermost coils (base temperature) and that of combustion gas in the outer cover (bell temperature). It is, therefore, extremely difficult to accurately estimate the temperature of coils on base stools solely on the basis of these data. For this reason, in practical furnace control, a heating pattern to ensure the soaking

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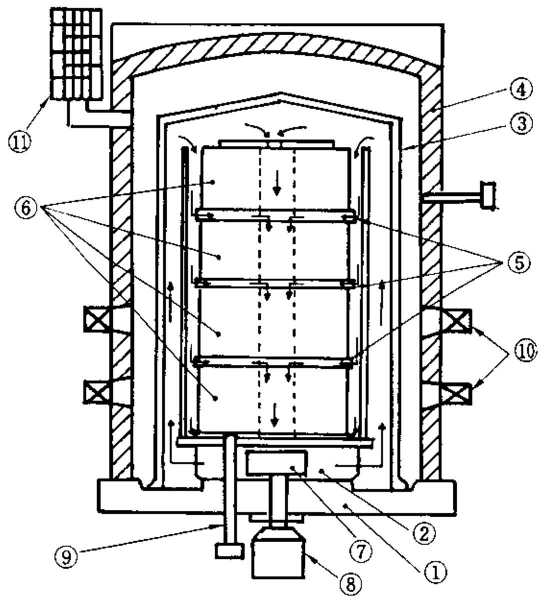
** Mizushima Works



① Base plate ⑤ Convector plate ⑨ Thermocouple
② Diffuser ⑥ Coil ⑩ Burner
③ Inner cover ⑦ Re-circulating fan ⑪ Recuperator
④ Outer cover ⑧ Re-circulating fan motor

Fig. 1 Schema of single-stack batch annealing furnace

temperature and time (base temperature control system) was adopted so as to carry out annealing with a certain margin of surplus energy.

3 Heat Transfer Simulation Modal

In the batch annealing furnace, it is difficult, as stated above, to know the exact internal status of the furnace from the temperature information transmitted to the outside. Therefore, a heat transfer simulation model has been developed for the purpose of elucidating the phenomenon in the furnace.

3.1 Flow Rate Distribution of Atmospheric Gas within Inner Cover

First, in order to clarify rheological phenomena⁵⁾ within the inner cover, a 1/3 scale acrylic model of an annealing furnace was made as shown in **Fig. 2**. With this model, the flow of atmospheric gas was quantitatively grasped, and factors for pressure drop caused by deflecting, branching⁶⁾⁷⁾ and joining in the recirculation path of atmospheric gas were calculated. Particularly, the joining of branch flow influxing radially from the convector plate to the flow caused by the rotation of coil's core is a phenomenon peculiar to the batch annealing furnace.

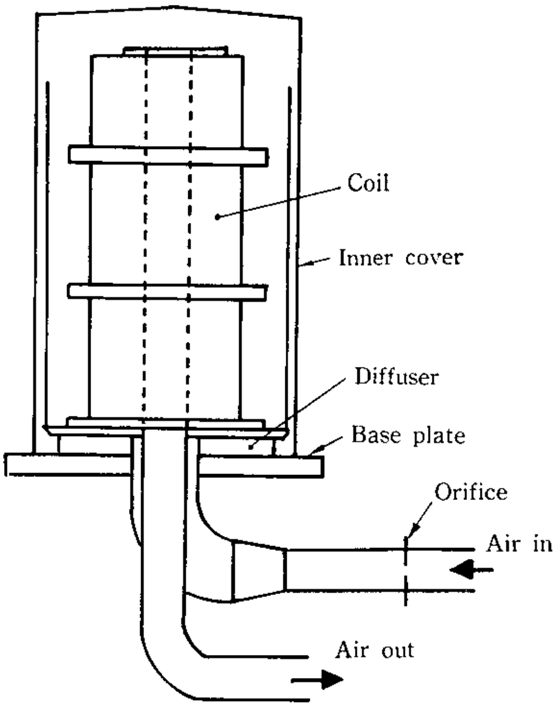
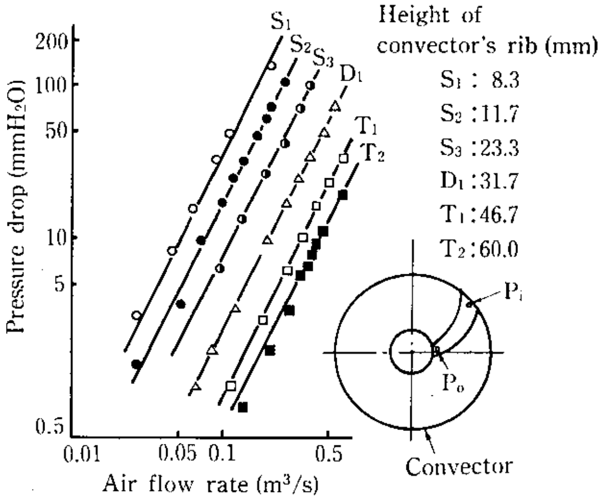


Fig. 2 Model equipment with 1/3 scale of batch annealing furnace



P_i, P_o : Pressure measuring point

Fig. 3 Relation between air flow rate and pressure drop in convector

The flow rate distribution within the inner cover was measured with the hot wire anemometer and differential flowmeters. In the latter method, the relationship of the flow rate around each convector plate to the pressure drop across the convector plate is determined previously, and the flow rate in the actual system is obtained from the pressure drop value measured at the actual stack of coils and convector plates (see **Fig. 3**). These procedures provide various pressure drop factors and make it possible to prepare a simulation model for predicting the rheological phenomena within the inner cover.

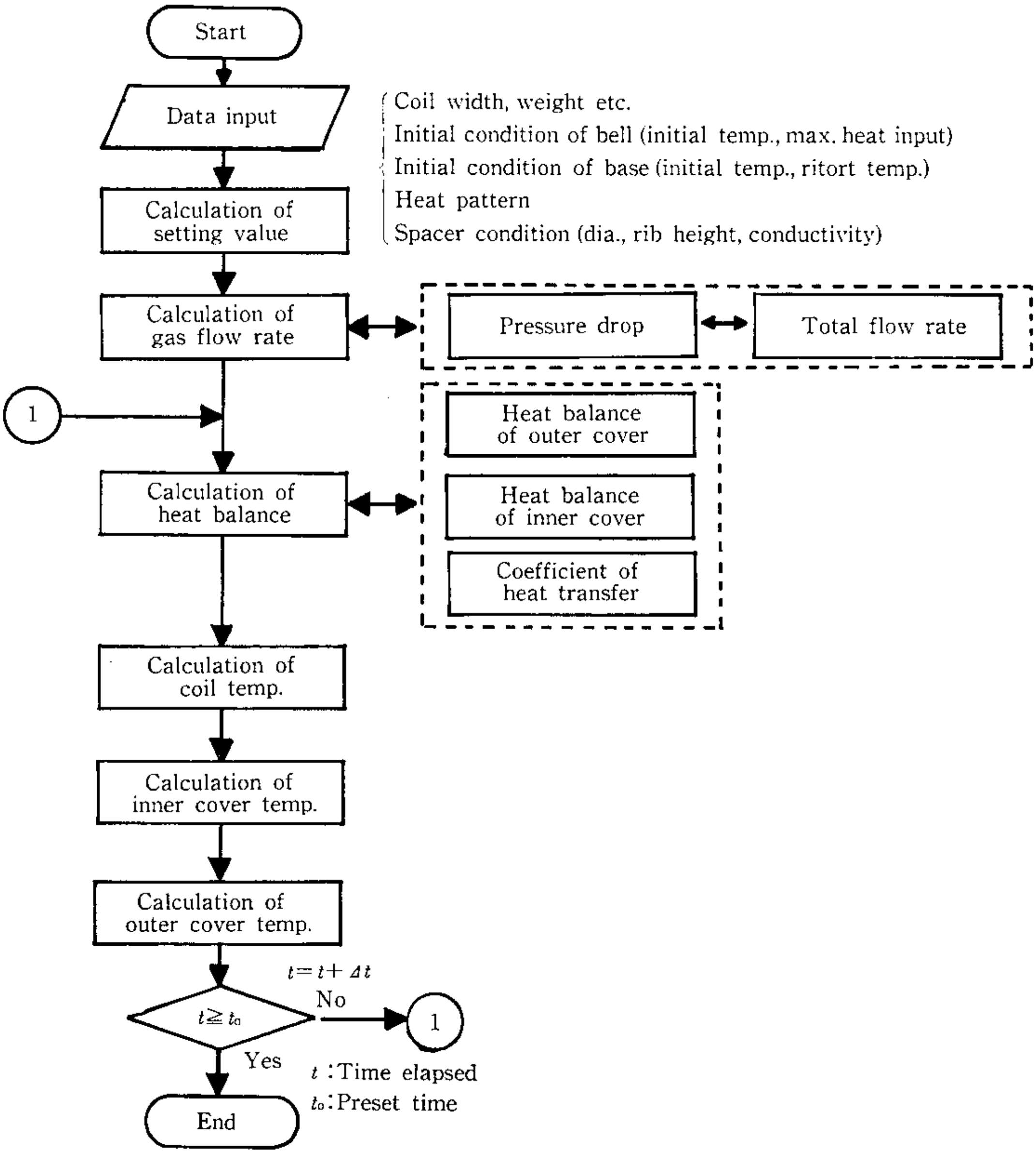
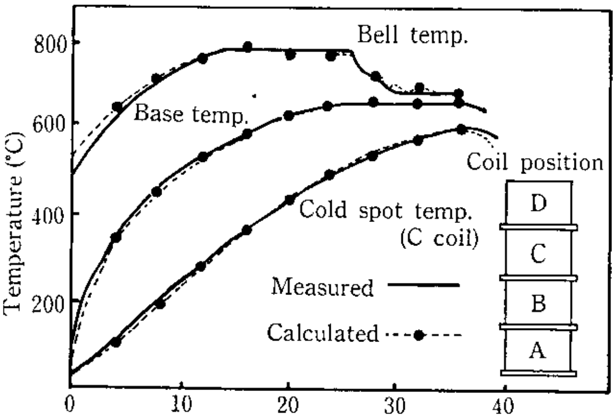


Fig. 4 Flow diagram for calculation of furnace temperature by calculation model

3.2 Outline of Simulation Model

For the atmospheric gas in the annealing furnace, the temperature distribution in various parts was calculated on the basis of heat balance for minute volume elements. A heat transfer simulation model was developed to determine the boundary conditions around the coil on the basis of these data and to calculate the temperature distribution collectively for coil, convector plate, inner cover and outer cover. A flow chart for the calculation is shown in **Fig. 4**. The flow rate of atmospheric gas around the convector plates and coils is determined on the basis of drops in the pressure balance in various flow paths in consideration of the characteristic curves of the recirculation fan. If the flow rates at various parts are known, the coefficient of convection heat transfer can be calculated to determine the boundary conditions around the coil. The temperature distribution around coil, convector plate, inner cover and outer cover is calculated by using differential equations.

The calculated temperature derived from the simulation model is compared with the measured temperature in **Fig. 5**. For the base temperature, bell temperature and cold spot temperature of coils on base stools, the calculated values coincided well with the measured values. (**Fig. 5** shows a coil base stool.) With this model, it is possible to calculate the fuel flow and the current consumption of the base fan motor, in addition to the temperature distribution, permitting the study



Coil width (mm) A:1 200, B:1 000, C:800, D:900

Fig. 5 Comparison between measured and calculated temperatures

of optimum operational procedures for the annealing furnace from various angles.

4 Coil Annealing Prediction System

In the batch annealing furnace, its peculiar structural design makes it so that the heat-up rate differs depending upon the stacked position, as stated above. The cold spots are inaccessible to direct thermometry because they are located within the coil. Even when placed on the same base stool, the heat-up rates may differ depending upon the coil conditions (such as weight and width of coil). For this reason, in the conventional annealing furnace control, a heat cycle has been adopted on the safer side in consideration of the fluctuation in charge arrangement.

In the coil annealing prediction system developed recently, the cold spot temperature of each coil stacked is estimated with high precision by using a highly accurate heat transfer model, with heating terminated when the cold spot temperatures of every coil attain the target level. Since the process computer used for the control has inadequate capacity for applying the heat transfer model as it is, the latter is simplified to a control model suited for practical operation.

4.1 Basic Equation for Coil Annealing Prediction

When an object is left in atmospheric gas at temperature T_0, the following relationship is obtained between the temperature of the object T and time t, with the temperature difference within the object ignored,

$$hA(T_O - T) = C_P W \cdot \frac{dT}{dt} \quad \cdots\cdots\cdots\cdots\cdots (1)$$

Hence, $\log(T_O - T) = -\frac{hA}{C_P W}t + C \quad \cdots\cdots\cdots (2)$

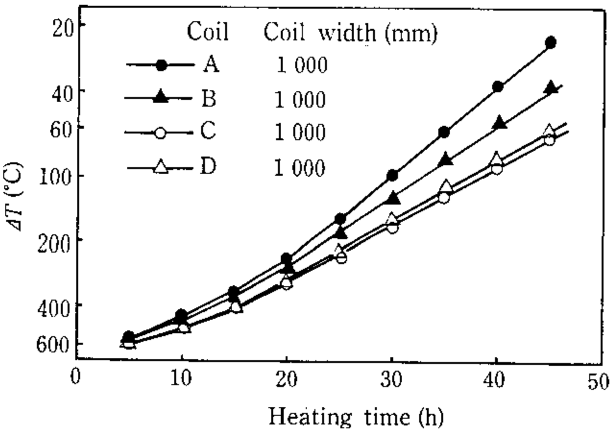


Fig. 6 Relation between $\Delta T (= T_S - T_{CS})$ and heating time for each coil (T_S: Soaking temp., T_{CS}: Cold spot temp.)

h: Heat transfer rate
A: Surface area of object
C_P: Specific heat
W: Weight of object
T_O: Temperature of atmospheric gas
C: Constant

The relationship of logarithm of temperature difference, $\Delta T = T_O - T$ measured using a 1/3 scale model with T_O and T approximated by means of the soaking temperature and cold spot temperature, respectively, to the heating time is shown in **Fig. 6**. After the temperature of atmospheric gas in the inner cover reaches a certain level, the temperature may be regarded as rising linearly. Thus, the basic formula for the coil annealing prediction is represented by eq. (3).

$$t = \frac{\log(T_S - T_{CS}) - \alpha}{\beta} \quad \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

T_S: Soaking temperature
T_{CS}: Target cold spot temperature
t: Time from starting prediction to attaining target cold spot temperature
α, β: Constants

Two constants α and β are represented as a function of coil width and weight of each coil stacked, and heating capacity of furnace. They are determined by the multi-regression analysis from the results of calculations with the heat transfer simulation model.

4.2 Equations for Coil Annealing Prediction

These predictory equations are constructed for different annealing conditions (such as soaking temperature and charge size). As an example, a set of predictory equations for a large 4-base stack charge is shown below.

$$\text{Base A: } t_{A} = \frac{(2.552 + 0.123X_{A} - 0.008H_{F})}{(5.891 - 1.361X_{A} - 0.145X_{D}}$$

$$\frac{-\cdot\log(T_{S} - T_{CS})}{+ 0.004W_{D} - 0.092H_{F}) \times 10^{-2}} \cdot\cdot(4)$$

$$\text{Base B: } t_{B} = \frac{(2.618 - 0.035X_{A} + 0.159X_{B}}{(5.753 - 1.981X_{B} - 0.439X_{C}}$$

$$\frac{- 0.011H_{F}) - \log(T_{S} - T_{CS})}{- 0.276X_{D}) \times 10^{-2}} \cdot\cdot(5)$$

$$\text{Base C: } t_{C} = \frac{(2.649 - 0.027X_{A} + 0.155X_{C}}{(4.998 + 0.482X_{A} - 1.839X_{C}}$$

$$\frac{- 0.001H_{F}) - \log(T_{S} - T_{CS})}{- 0.211X_{D} - 0.006W_{t}) \times 10^{-2}} \cdot\cdot(6)$$

$$\text{Base D: } t_{D} = \frac{(2.863 - 0.064X_{A} + 0.082X_{D}}{(5.779 + 0.243X_{A} - 0.163X_{C}}$$

$$\frac{- 0.002W_{t}) - \log(T_{S} - T_{CS})}{- 1.144X_{D} + 0.058H_{F}) \times 10^{-2}} \cdot\cdot(7)$$

X_{A}: Coil width of Base A (bottom stage)
X_{B}: Coil width of Base B
X_{C}: Coil width of Base C
X_{D}: Coil width of Base D
W_{t}: Charge weight
H_{F}: Heating capacity of furnace
T_{S}: Soaking temperature
T_{CS}: Target cold spot temperature
t_{A}-t_{D}: Predicted time

The accuracy of cold spot temperature at the predicted time as calculated from these coil annealing prediction equations was within ±5°C. In the practical operation, the time at which the cold spot temperature of coil of each base attains the target level is calculated by eq. **(3)** when the gradient of temperature rise enters the linear range as shown in **Fig. 6**, and heating is finished at this time.

5 Efficient Charge Scheduling

Judgement on the completion of annealing for coils in each base has turned out accurate by using the coil annealing prediction equations. In order to enhance the furnace efficiency, it is necessary to prevent individual coils in the same charge from being overheated. For this purpose, it is necessary to derive the stacking conditions (coil width, weight and target temperature) under which cold spot temperatures of coils on fase stools attain respective targets in the same annealing time from the moment of ignition. This can be achieved from the predictory equations given in the above. An example is shown in **Table 1**. It has become possible to obtain a highly efficient charge scheduling through calculation of the optimum coil width.

6 Results of Practical Furnace Operation

6.1 Cold Spot Temperature

The fluctuation of cold spot temperatures at the end of annealing was widely reduced through the application of CAPS. As shown in **Fig. 7**, the fluctuation in the conventional base temperature control system was as large as 20°C in standard deviation. The application of CAPS allowed the fluctuation to be reduced to 5°C.

6.2 Product Quality

The mechanical properties of coils annealed through the application of CAPS at the location of cold spots were measured and the results are shown in **Fig. 8**.

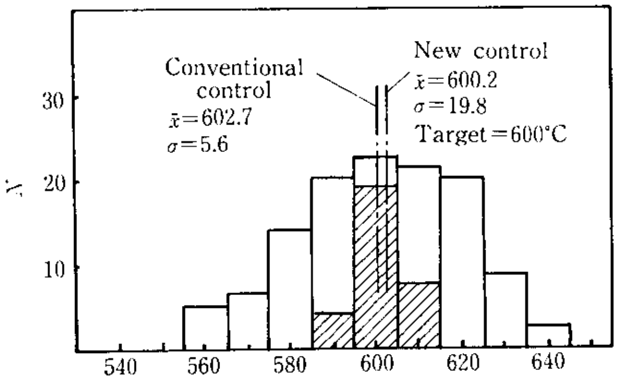
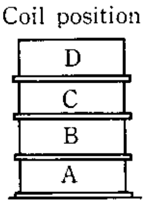


Fig. 7 Comparison of cold spot temperature between new and conventional control methods

Table 1 An example of best stacking order

Coil A (mm)	Coil B (mm)	Coil C (mm)	Coil D (mm)	Heating time (h)	Charging weight (t)
1 200	1 048	812	942	33.05	150.2
1 225	1 071	837	981	33.86	154.4
1 250	1 094	863	1 021	34.70	158.7
1 275	1 117	889	1 060	35.57	162.9



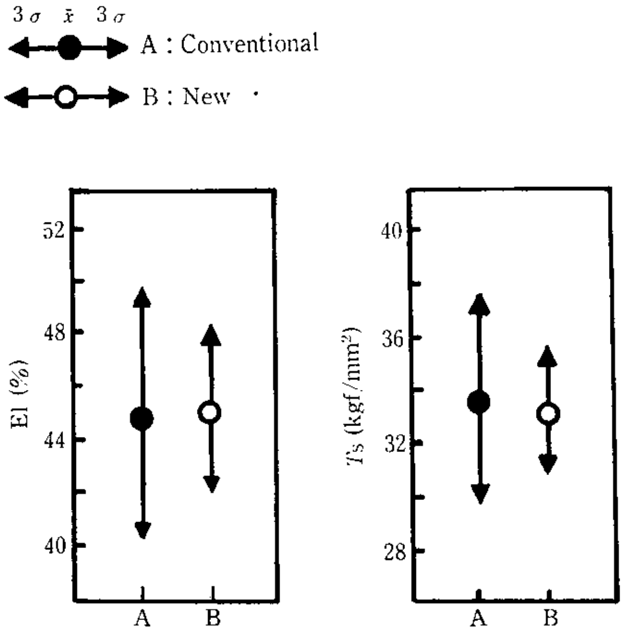


Fig. 8 Comparison of mechanical properties between conventional and new methods

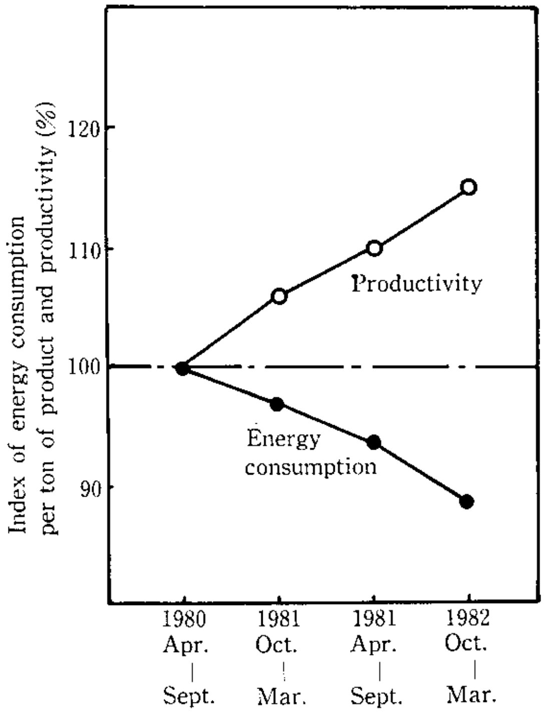


Fig. 9 Yearly change in energy consumption per ton of product and productivity

The fluctuation was suppressed also quality. This is due to the reduction of fluctuation in the cold spot temperature as described in the above, and the remaining fluctuation may be attributed to the variation in chemical composition and hot rolling conditions.

6.3 Energy Consumption and Efficiency

As shown in **Fig. 9**, the anneal energy consumption has been progressively reduced since the application of CAPS, allowing energy savings per ton of product as great as 10%. Moreover, the annealing efficiency was improved by 15%. These achievements could be achieved by reducing the fluctuation in cold spot temperature of stacked coils on the same base stools in the same charge and eliminating superfluous heating.

7 Conclusion

The development of CAPS allowed accurate estimation of cold spot temperature of stacked coils. This had hitherto been regarded as very difficult, and the annealing technology was markedly improved. Through the application of CAPS, the fluctuation of cold spot temperature of stacked coils on base stools could be reduced, heating was performed efficiently, the mechanical properties were stabilized, the energy consumption per ton of product was reduced by 10% or more and the annealing efficiency was improved by about 15%. Moreover, the annealing cycle which previously had to be subdivided was readily grouped by setting a target temperature, thereby improving the workability for charge scheduling.

The heat transfer simulation model which provided the base for the development of the CAPS allows calculation of the fuel gas flow rate and the base fan motor current consumption in addition to the temperature distribution in coils, thereby providing the means to study the optimum operation of the annealing furnace from various angles.

In order to improve the performance of CAPS further, it seems to be necessary to elucidate the total effect of various factors governing the product quality, such as chemical composition, hot-rolling conditions, cold reduction and quenching temperature, and to develop a cold rolled strip quality control system which controls the mechanical properties of cold rolled strip by controlling the annealing temperature at the final annealing process in consideration of the metallurgical conditions in the preceding processes.

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