Strip Tension Control Considering the Temperature Change in Multi-Span Systems

Chang Woo Lee
Department of Mechanical Engineering, Konkuk University, 1 Hwayang-Dong, Gwangjin-Gu, Seoul 143-701, Korea
Kee Hyun Shin*
Department of Mechanical and Aerospace Engineering, Konkuk University, 1 Hwayang-Dong, Gwangjin-Gu, Seoul 143-701, Korea

The mathematical model for tension behaviors of a moving web by Shin (2000) is extended to the tension model considering the thermal strain due to temperature variation in furnace. The extended model includes the terms that take into account the effect of the change of the Young's Modulus, the thermal coefficient, and the thermal strain on the variation of strip tension. Computer simulation study proved that the extended tension model could be used to analyze tension behaviors even when the strip goes through temperature variation. By using the extended tension model, a new tension control method is suggested in this paper. The key factors of suggested tension control method include that the thermal strain of strip could be compensated by using the velocity adjustment of the helper-rollers. The computer simulation was carried out to confirm the performance of the suggested tension control method. Simulation results show that the suggested tension control logic not only overcomes the problem of the traditional tension control logic, but also improves the performance of tension control in a furnace of the CAL (Continuous Annealing Line).

Key Words: Temperature Change, Tension Control, Thermal Coefficient, Thermal Strain

Nomenclature

A : Cross-sectional area of web
E : Young's modulus
L : Length of span
T : Change in the web tension from a steady-state operating value
t : Tension of web
V : Change in the web velocity from a steady-state operating value
v : Velocity of roller
α : Thermal coefficient
β : Velocity difference
ε : Strain of web
ε^{th} : Thermal strain
ε^{e} : Elastic strain
θ : Temperature
ρ : Density of web

Subscript

eq : Equivalent
N : Index
op : Steady-state operating value
θ : Temperature

1. Introduction

Continuous annealing line (CAL) is often composed of several sections for heating or cooling the material (rolled steel). A typical configuration of the CAL usually consists of preheating section (PHS), heating section (HS), soaking sec-

* Corresponding Author,
E-mail: khshin@konkuk.ac.kr
TEL: +82-2-450-3072; **FAX**: +82-2-447-5886
Department of Mechanical and Aerospace Engineering, Konkuk University, 1 Hwayang-Dong, Gwangjin-Gu, Seoul 143-701, Korea. (Manuscript **Received** October 23, 2004; **Revised** February 18, 2005)

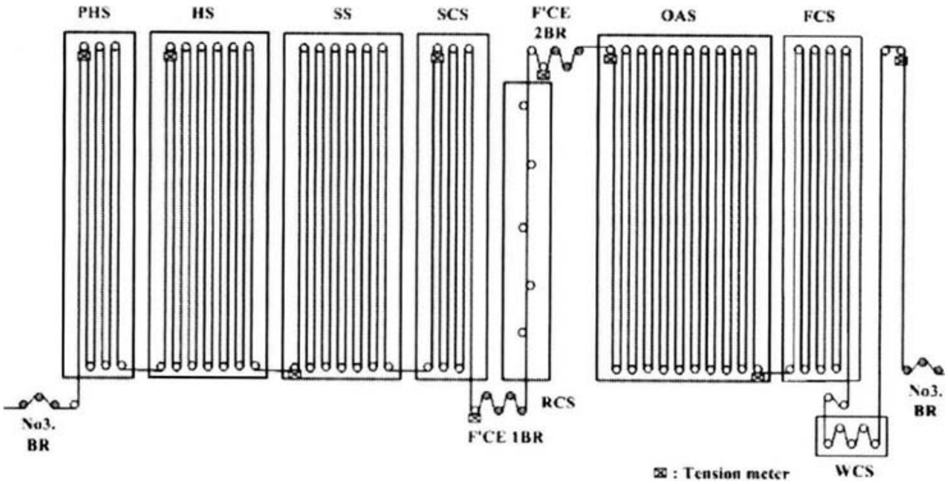

Fig. 1 Configuration of continuous annealing line

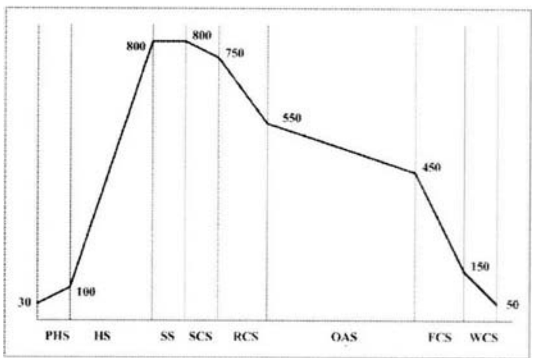

Fig. 2 Typical temperature distribution of a CAL

tion (SS), slow cooling section (SCS), rapid cooling section (RCS), over aging section (OAS), final cooling section (FCS), and water cooling section (WCS) as shown in Fig. 1. Generally the temperature distribution of the CAL is a little different depending on the product material, but a typical temperature distribution looks like the one in Fig. 2.

The CAL consists of several hundreds of rollers as shown in Fig. 1. The line speed and web tension are usually regulated at the position of tension meter in the CAL by using the motors connected to each roll (POSCO, 1998). However while the web passes through each section, thermal strain takes place in a web because of temperature difference between the in-let and the out-let of each section, and at the same time the Young's Modulus of material varies as well. Such thermal strain and the change in the Young's Modulus act as a disturbance for the control of tension and speed. Hence the performance of controller might be degraded because of such a thermal effect. Moreover, even when the tension of material is controlled well at each position where the tension meter is installed, the tensions in other spans may be far away from their desired value due to the thermal strain in each section. Therefore a slippage may occur between the roller and the web due to the excessive tension difference between adjacent spans in a section.

Consequently in order to improve productivity and quality of product, it is important to develop the tension control method considering the thermal effect in multi-span systems with temperature change. In this paper, a mathematical model for tension behaviors of a moving web by Shin is extended to the tension model which includes the thermal effect on the tension variation. By using the model developed, a new control logic that includes velocity compensator is suggested in order to eliminate thermal effect due to temperature change in a section. The computer simulation study was carried out to confirm the performance of the suggested tension control method. Simulation results show that the suggested tension control logic not only overcomes the problem of the traditional tension control logic, but also improves the performance of tension control in a furnace of the CAL.

2. Limitation of Established Tension Model

The law of conservation of mass for the control volume as shown in Fig. 3 can be written such as Eq. (1) (Shin, 2000).

$$\frac{d}{dt}\left(\int_0^L \rho(x,t)A(x,t)\,dx\right) = \rho_1(t)A_1(t)v_1(t) - \rho_2(t)A_2(t)v_2(t) \quad (1)$$

From Eq. (1), a nonlinear tension model by Shin (Shin, 2000; Shin and Hong, 1998) can be developed such as Eq. (2).

$$L_2\frac{d}{dt}(t_2(t)) = v_1(t)t_1(t) - v_2(t)t_2(t) + EA(v_2(t) - v_1(t)) \quad (2)$$

Eq. (2) describes tension behavior for one-span web transport system when the temperature of the web is constant. But in the case of considering temperature change of strip as shown in Fig. 4, Eq. (2) can not properly describe tension behavior for the strip because the Young's Modulus and thermal strain of the strip is not uniform within the web span anymore. Therefore the mathematical model must include the following terms to properly describe tension behavior considering temperature change of the web.

(1) The thermal strain due to temperature change.

(2) The Young's Modulus variation due to temperature change.

(3) The thermal coefficient variation due to temperature change.

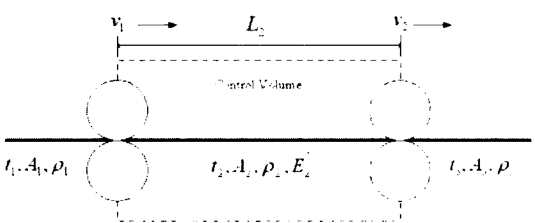

Fig. 3 One-span web transport system

3. Tension Model Considering Temperature Change

To develop the tension model considering thermal effect, the following assumptions were made.

(1) The temperature distribution within the web span as shown in Fig. 4 is in steady-state, therefore it is not a function of time t (Jeong et al., 1990).

(2) The variation of temperature distribution can be ignored due to the small velocity change from a steady-state operating value.

(3) The strain within a web is linear combination of elastic strain and thermal strain.

(4) The web cross-section does not vary along the web.

An equivalent strain within a web span in Fig. 4 is defined such as Eq. (3).

$$\varepsilon_{eq}(t) = \frac{1}{L}\int_0^L \varepsilon(x,t)\,dx \quad (3)$$

where $\varepsilon(x,t)$ is strain of infinitesimal element dx as shown in Fig. 4. Under assumption 1) and 3), Eq. (3) can be rewritten as Eq. (4)

$$\begin{aligned}\varepsilon_{eq}(t) &= \frac{1}{L}\int_0^L \varepsilon(x,t)\,dx \\ &= \frac{1}{L}\int_0^L (\varepsilon^e(x,t) + \varepsilon^{th}(x))\,dx \\ &= \frac{1}{L}\int_0^L \varepsilon^e(x,t)\,dx + \frac{1}{L}\int_0^L \varepsilon^{th}(x)\,dx \\ &= \varepsilon^e_{eq}(t) + \varepsilon^{th}_{eq}\end{aligned} \quad (4)$$

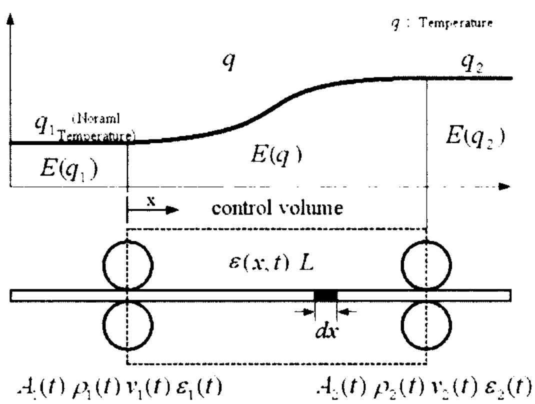

Fig. 4 A web span in temperature change

ε_{eq}^{e} in Eq. (4) can be written as Eq. (5)

$$\varepsilon_{eq}^{e}(t)=\frac{1}{L}\int_0^L \varepsilon^e(x,t)\,dx = \frac{t(t)}{AL}\int_0^L \frac{1}{E(x)}dx \quad (5)$$

Defining an equivalent Young's Modulus as Eq. (6), and calculating ε_{eq}^{th} by using substituting thermal coefficient α, then Eq. (4) can be written for ε_{eq} within an infinitesimal element dx as Eq. (7).

$$E_{eq}=\frac{L}{\int_0^L \frac{1}{E(x)}dx} \quad (6)$$

$$\varepsilon_{eq}(t)=\varepsilon_{eq}^{e}(t)+\varepsilon_{eq}^{th} = \frac{t(t)}{AE}+\frac{1}{L}\int_0^L \alpha(x)(\theta(x)-\theta_1)\,dx \quad (7)$$

From Eq. (1) and Eq. (3), we can get Eq. (8) that represents a dynamic relationship between the web strain within the control volume and the velocity at the ends of the web span.

$$L\frac{d}{dt}(\varepsilon_{2eq}(t))=\varepsilon_1(t)v_1(t)-\varepsilon_{2eq}(t)v_2(t)+(v_2(t)-v_1(t)) \quad (8)$$

Combining Eq. (7) and Eq. (8) gives

$$L\frac{d}{dt}(t_2(t))=AE_{2eq}\varepsilon_1(t)v_1(t)-t_2(t)v_2(t)+AE_{2eq}(v_2(t)-v_1(t))-AE_{2eq}\varepsilon_{eq}^{th}v_2(t) \quad (9)$$

The tension $t(t)$ is identical to $t_2(t)$ (the tension at out-let of the control volume at Fig. 4) and $\varepsilon_2(t)$ is the strain at the in-let of control volume. Thus Eq. (9) can be written as Eq. (10).

$$L\frac{d}{dt}(t_2(t))=\frac{E_{2eq}}{E_{\theta 1}}t_1(t)v_1(t)-t_2(t)v_2(t)+AE_{2eq}(v_2(t)-v_1(t))-AE_{2eq}\varepsilon_{2eq}^{th}v_2 \quad (10)$$

Eq. (10) can be linearized as Eq. (11) by using the perturbation method.

$$\frac{d}{dt}T_2(t)=\frac{v_{10}E_{2eq}}{LE_{\theta 1}}T_1(t)-\frac{v_{20}}{L}T(t)+\frac{AE_{2eq}}{L}(V_2(t)-V_1(t))-\frac{AE_{2eq}\varepsilon_{2eq}^{th}}{L}v_{20} \quad (11)$$

Eq. (11) is the mathematical model for tension behavior of a moving web considering the temperature change. Finally, multi-span model for tension control can be represented as follow Eq. (12).

$$\frac{d}{dt}T_N(t)=\frac{v_{N0}E_{N,eq}}{L_N E_{N-1,\theta}}T_{N-1}(t)-\frac{v_{N0}}{L_N}T_N(t)+\frac{AE_{N,eq}}{L_N}(V_N(t)-V_{N-1}(t))-\frac{AE_{N,eq}\varepsilon_{N,eq}^{th}}{L_N}v_{N0} \quad (12)$$

4. Proposed Control Scheme for Tension Regulation in a Section

Figure 5 is a typical configuration of a conventional control scheme for each section in the CAL. In the conventional control scheme, ATR (Automatic tension regulator) sends identical

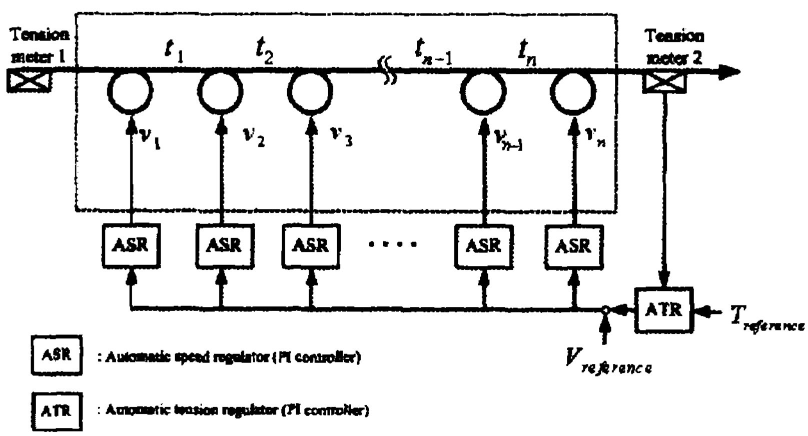

Fig. 5 A configuration for a section with conventional control scheme

signal (velocity reference) to each ASR (Automatic speed regulator) in order to regulate the tension at tension-meter 2 in Fig. 5. As a result, the velocity of each helper roll theoretically becomes identical with those of the other rolls in steady-state. Thus in the case of no temperature change in the section, the tension within the section converges to the one at the tension-meter 1 due to tension transfer. But in the case of temperature change in a section (for example, heating section), following problems might occur in tension regulation with the conventional control scheme.

(1) The tension at each span becomes different by the amount of the thermal strain due to temperature change of the material.

(2) Although the elastic strain of each span is equal, the tension of each span is not because the Young's Modulus varies according to temperature of the material.

As a result, although the tension at tension-meter 2 shown in Fig. 5 is regulated well by the ATR, the tension at the each span may not converge to the value of the tension-meter 1 as desired. The principal reason for that problem is that the velocity of each helper-roll becomes identical with others in steady-state regardless of the strain in those spans. For this reason, conventional control scheme may not suitable for regulating the tension in a section with tempera-

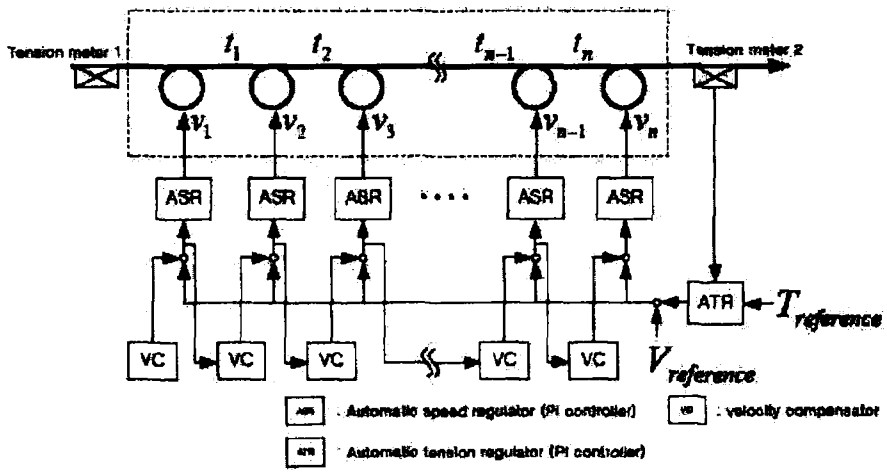

Fig. 6 The configuration for a section with proposed control scheme

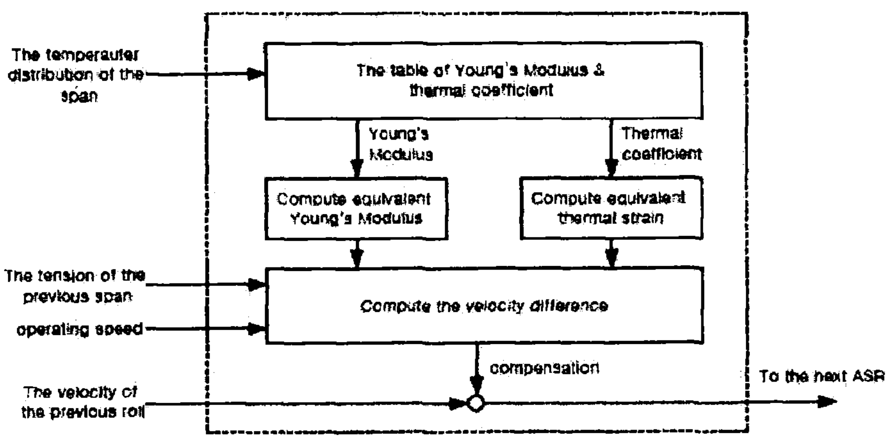

Fig. 7 The structure of the velocity compensator

ture change. Hence, a new control scheme is proposed as shown in Fig. 6. A key idea in the suggested control scheme is the velocity compensator which estimates the resultant tension variation due to the thermal effect and compensate that variation by changing the velocity of helper roll in advance. The structure of the velocity compensator is shown in Fig. 7. The velocity compensator computes equivalent thermal strain and equivalent Young's Modulus from a measured or estimated temperature distribution of each span. Then it transforms those into velocity difference between each roll in a web span using the Eq. (11). Finally, the velocity compensator adds velocity difference to velocity reference of the ASR to eliminate the tension variation due to temperature change in a web span. For example, assuming that the temperature distribution of each span, Young's Modulus, and thermal coefficient is linear for a specific temperature zone, then the velocity compensation term can be derived from Eq. (11) as following.

$$\beta_N = v_{op}\left\{\frac{T_{N-1}(t)}{A}\left(\frac{1}{E_{eq,N}}-\frac{1}{E_{\theta_{n-1}}}\right)+\varepsilon^{th}_{eq,N}\right\} \quad (13)$$

β_N in Eq. (13) is the value of velocity difference to be compensated between the roll at in-let and the one at out-let in one span, and it can be used to eliminate the Young's Modulus and thermal coefficient variation due to temperature change. Therefore, even with temperature change in the section, the tensions of each span converge to the one of upstream in steady-state by compensating the velocity difference β_N.

5. Simulation Results

A simulation study for the heating section and the final cooling section has been carried out in

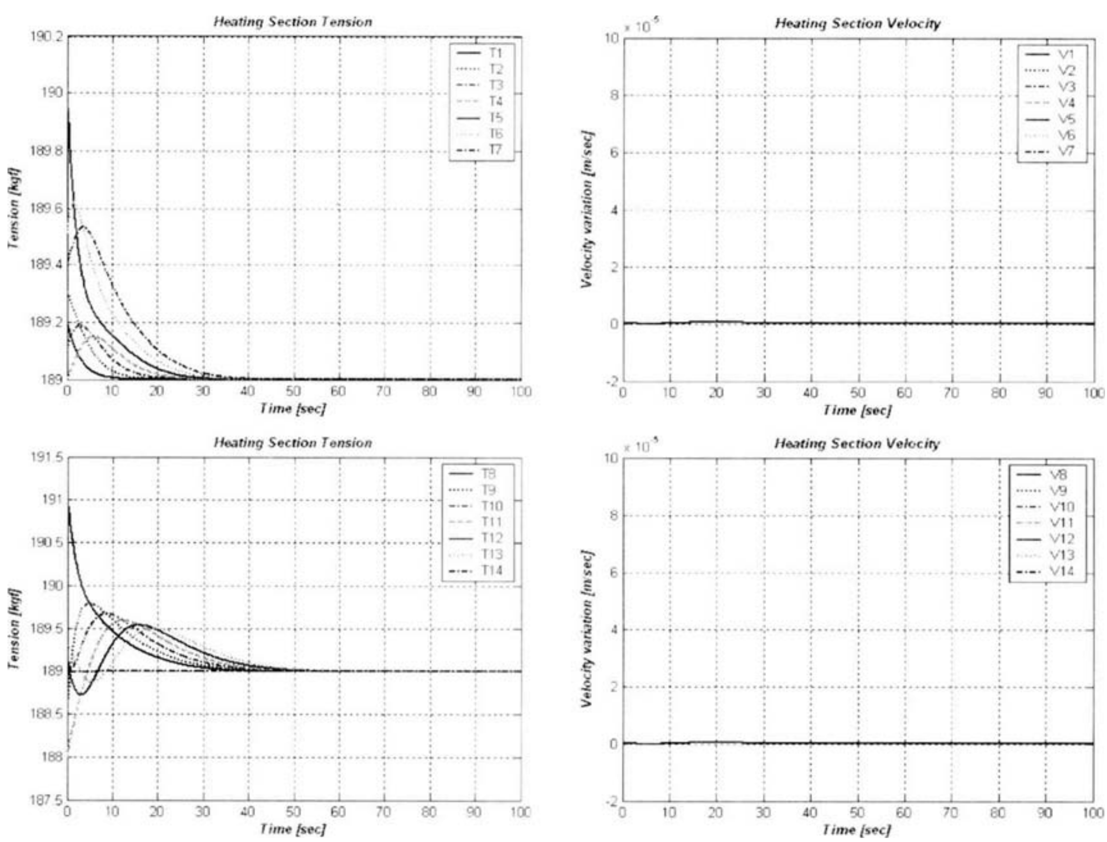

Fig. 8 The tension and velocity in heating section with conventional control scheme (no temperature change)

order to confirm the limitation of conventional control scheme and to verify the performance of the proposed control scheme. Because the temperature range of material in these section are larger than those of other sections, heating section and final cooling section were modeled as fourteen-span and six-span systems respectively. And it was assumed that the property of rolls and motors was identical within the system. The configuration of control scheme for heating section is same as that of Fig. 5 and Fig. 6. The configuration of control for the final cooling section is shown in Fig. 11. In heating section, the tension at the tension-meter 1 shown in Fig. 5 and Fig. 6 is 189 kgf (tension reference of heating section in CAL) and the tension reference of ATR is 163.24 kgf (tension reference of heating section in CAL). In final cooling section, the tension reference of ATR shown in Fig. 11 is 256.48 kgf (tension reference of final cooling section in CAL).

When the temperature is assumed to be uniform in the heating section, the tension and the velocity behaviors in the heating section are shown in Fig. 8. The tension of each span converges on the tension at tension-meter 1 (189 kgf). That is, the tension of each section can be regulated well by using conventional control scheme with no change in temperature. But on the other hand, assuming that there is temperature change in the material as shown in Fig. 2, the tension and the velocity behaviors in the heating section with conventional control scheme are shown in Fig. 9. Even t_{14} (at the tension-meter 2) is regulated well in steady-state, tensions in other spans are different from the tension at the tension-meter 1 because there is no velocity difference among helper rolls to remove thermal strain effect. Note that the negative tension does not necessarily represent compression but drooping.

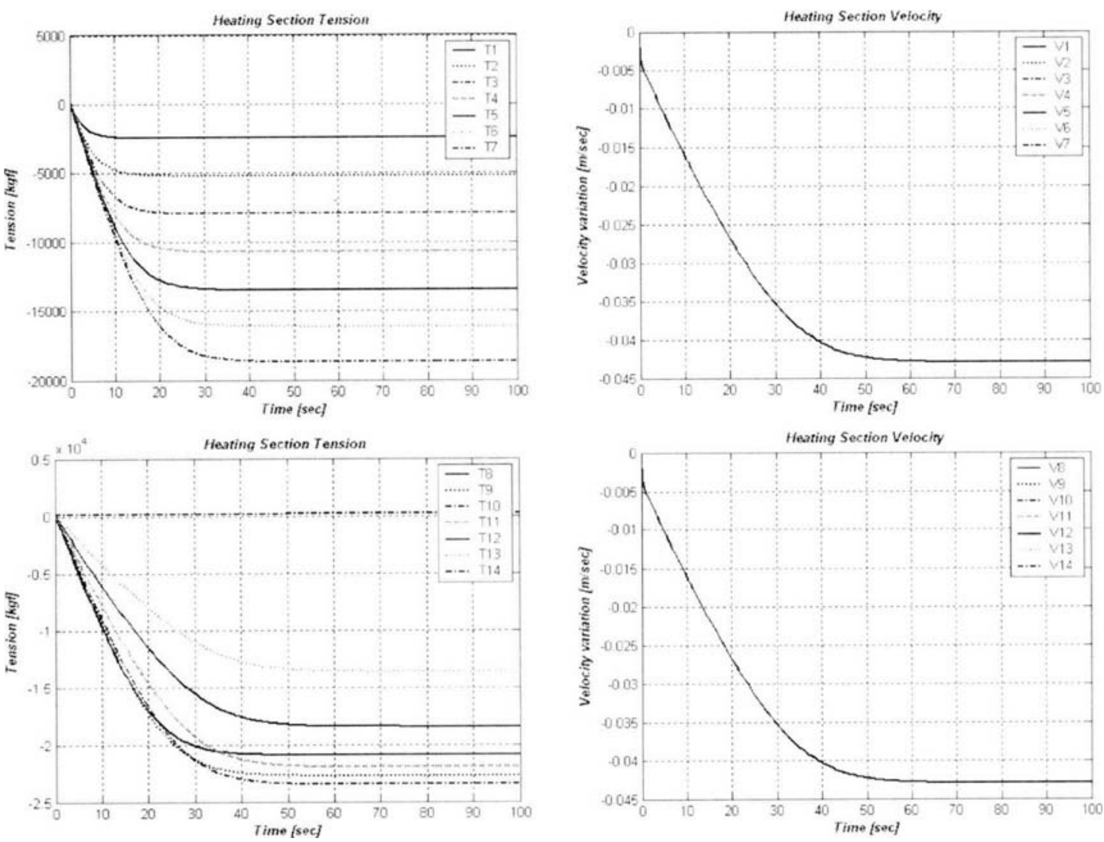

Fig. 9 The tension and velocity in heating section with conventional control scheme under temperature change

Fig. 10 shows the result of applying the proposed control scheme to the control of tension in the heating section. The results show that the velocity compensator works well even with thermal effect (thermal strain and varied Young's Modulus) on tension variation. The velocity of each roll varies to compensate the thermal effect and the tension of each span converged to the value at the tension-meter 1. Therefore in the case of applying the proposed control scheme to a heating section, the thermal effect due to temperature change can be eliminated.

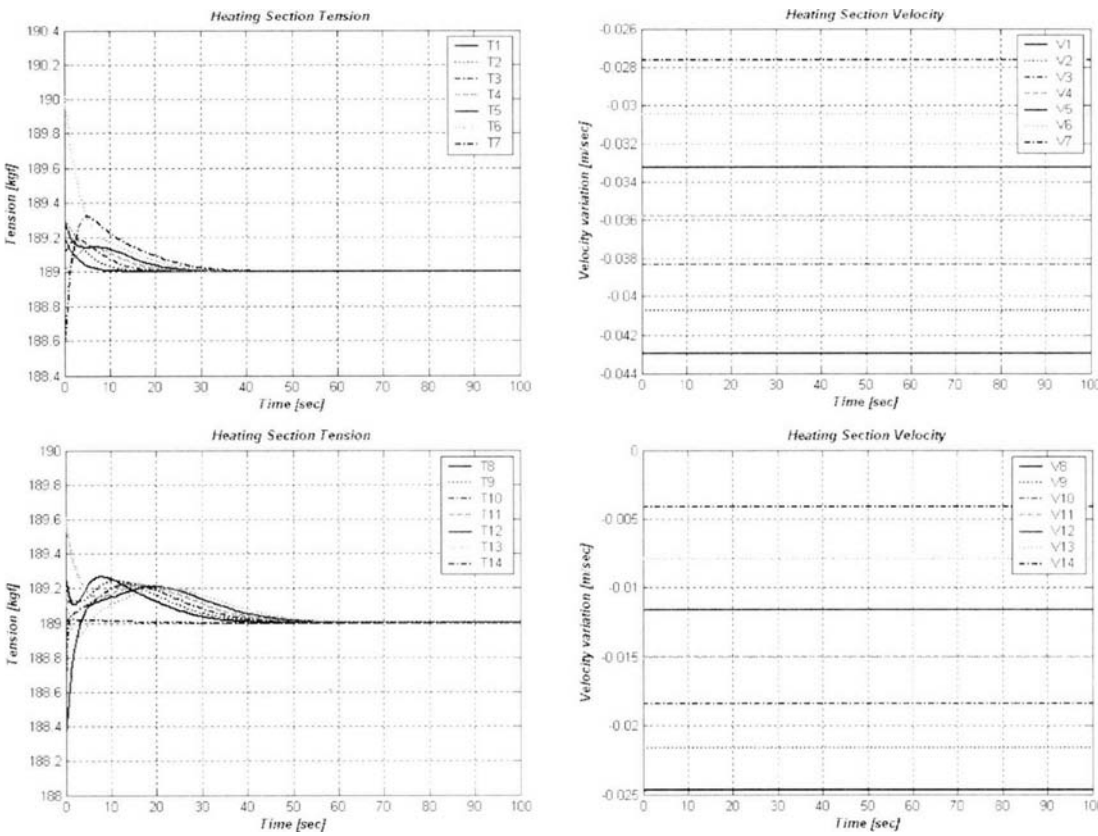

Fig. 10 The tension and velocity in heating section with proposed control scheme under temperature change

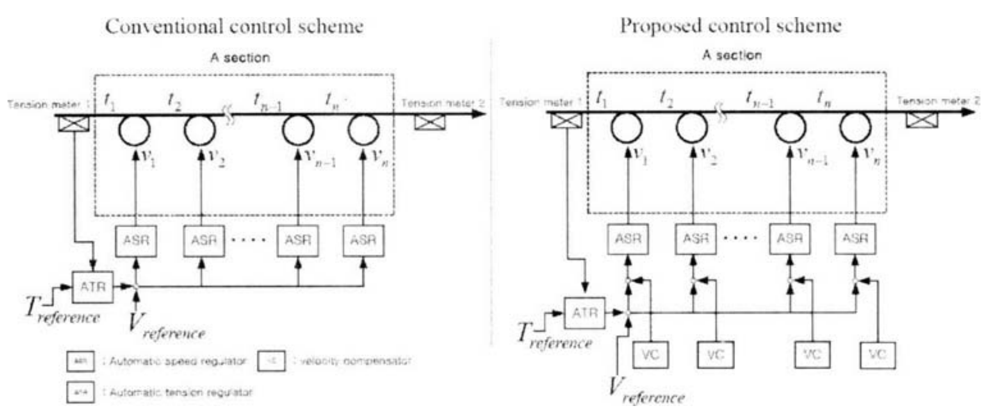

Fig. 11 Conventional control scheme and proposed control scheme in final cooling section

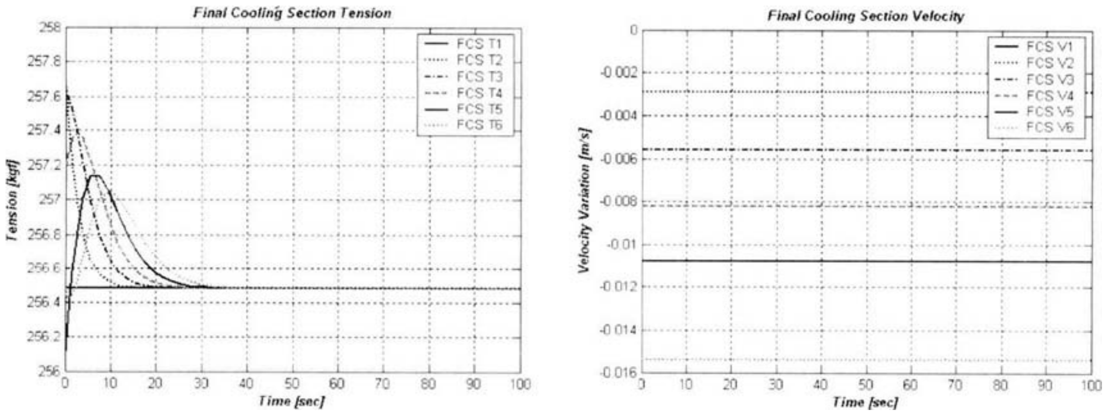

Fig. 12 The tension and velocity in final cooling section with conventional control scheme under temperature change

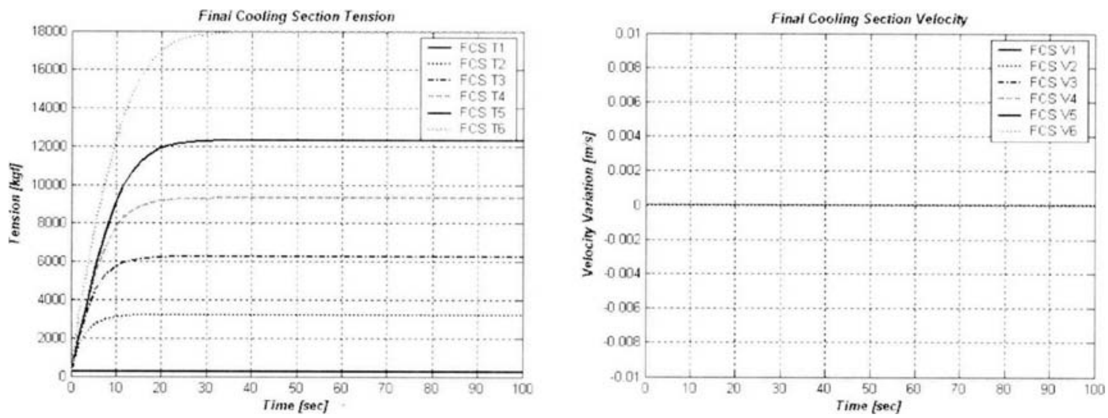

Fig. 13 The tension and velocity in final cooling section with proposed control scheme under temperature change

Figure 12 is the result of applying the conventional control scheme to a final cooling section. The tension is increased in the section because the material is cooled. The velocity converges to the same value in the same way as in the heating section. Fig. 13 is the result of applying the proposed control scheme to the final cooling section. The tension of each span is maintained at a desired value in steady-state because of the velocity compensation in the same way as those in the heating section.

6. Conclusions

In this paper, a mathematical model for tension behavior considering temperature change is developed in order to study tension behavior of the plants with heating or cooling materials just like in the CAL. Using the mathematical model developed, we demonstrated that it is impossible to regulate the tension in a section by using the conventional control scheme. A new control scheme including velocity compensator for the CAL is proposed in order to overcome the problems of the conventional control scheme.

In order to verify the performance of proposed control scheme, computer simulation study was carried out for a section with temperature change. From the computer simulation study, it is confirmed that the tension variation due to temperature change could be eliminated well by the proposed control scheme in the CAL.

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