

STRIP TENSION CONTROL CONSIDERING THE THERMAL STRAIN IN MULTI-SPAN SYSTEMS WITH TEMPERATURE CHANGE

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ABSTRACT

The mathematical model for tension behaviors of a moving web by Shin [1] 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 study was carried out to confirm the performance of the suggested tension control method. Simulation results shows 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).

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
ρ	Density of web
β	Velocity difference
ε	Strain of web
ε^{th}	Thermal strain
ε^e	Elastic strain
θ	Temperature

Subscript

<i>eq</i>	Equivalent
<i>N</i>	Index
<i>op</i>	Steady-state operating value
θ	Temperature

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 section(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 [4]. 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 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 shows 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.

LIMITATION OF ESTABLISHED TENSION MODEL

The law of conservation of mass for the control volume shown in Fig. 3 can be written as follows.

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

From equation {1}, a nonlinear tension model by Shin [1] can be developed as follows.

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

Equation{2} describes tension behavior for an 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, equation{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.

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 [2].
- 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 as equation{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 shown in Fig. 4.

Under assumption 1) and 3), equation{3} can be rewritten as

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

$\varepsilon_{eq}^e(t)$ in equation{4} can be written as

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

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

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

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

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

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

Combining equation{7} and {8} gives

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

The tension $t(t)$ is identical to $t_2(t)$ (the tension at out-let of the control volume at Fig. 4) and $\varepsilon_1(t)$ is the strain at the in-let of control volume. Thus equation{9} can be written as equation{10}.

$$L \frac{d}{dt} (t_2(t)) = \frac{E_{eq}}{E_{\theta_1}} t_1(t)v_1(t) - t_2(t)v_2(t) + AE_{eq}(v_2(t) - v_1(t)) - AE_{eq} \varepsilon_{eq}^{th} v_2(t) \quad \{10\}$$

where $\varepsilon_{eq}^{th} = \frac{1}{L} \int_0^L \alpha(x)(\theta(x) - \theta_1) dx$.

Equation{10} can be linearized as equation{11} by using the perturbation method.

$$\frac{d}{dt} T_2(t) = \frac{v_{10} E_{eq}}{L E_{\theta_1}} T_1(t) - \frac{v_{20}}{L} T_2(t) + \frac{A E_{eq}}{L} [V_2(t) - V_1(t)] - \frac{A E_{eq} \varepsilon_{eq}^{th}}{L} v_{20} \quad \{11\}$$

where $\varepsilon_{eq}^{th} = \frac{1}{L} \int_0^L \alpha(x)(\theta(x) - \theta_1) dx$.

Equation{11} is the mathematical model for tension behavior of a moving web considering the temperature change.

PROPOSED CONTROL SCHEME FOR TENSION REGULATION IN A SECTION

Fig. 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 signal(velocity reference) to each ASR(Automatic speed ragulator) 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 problems 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 temperature 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 equation{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 equation{11} as following.

$$\beta_N = v_{op} \left\{ \frac{T_{N-1}(t)}{A} \left(\frac{1}{E_{eq,N}} - \frac{1}{E_{\theta_{n-1}}} \right) + \varepsilon_{eq,N}^{th} \right\} \quad \{12\}$$

β_N in equation{12} 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 tension of each span converge to the one of upstream in steady-state by compensating the velocity difference β_N .

COMPUTER SIMULATION

A simulation study for the heating section and the final cooling section has been carried out in 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-spans and six-spans systems respectively. And it was assumed that the property of rolls and motors was identical within the system. The configuration of heating section is same as that of Fig. 5,6 The configuration of the final cooling section is shown in Fig. 11. In heating section, the tension at the tension-meter 1 shown in Fig. 5,6 is 189kgf and the tension reference of ATR is 163.24kgf. In final cooling section, the tension reference of ATR shown in Fig. 11 is 256.48kgf.

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(189kgf). 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. 10 shows the result of applying the proposed control scheme to the control of tension in the heating section. The results shows 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. 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 thanks to the velocity compensation in the same way as those in the heating section.

CONCLUSION

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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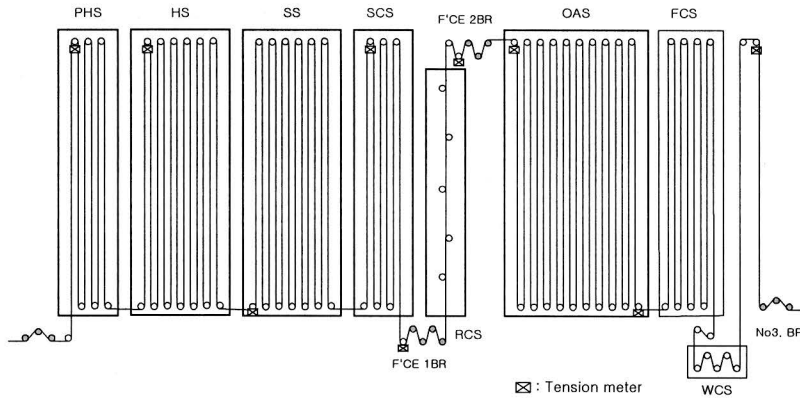


Fig. 1. Configuration of continuous annealing line

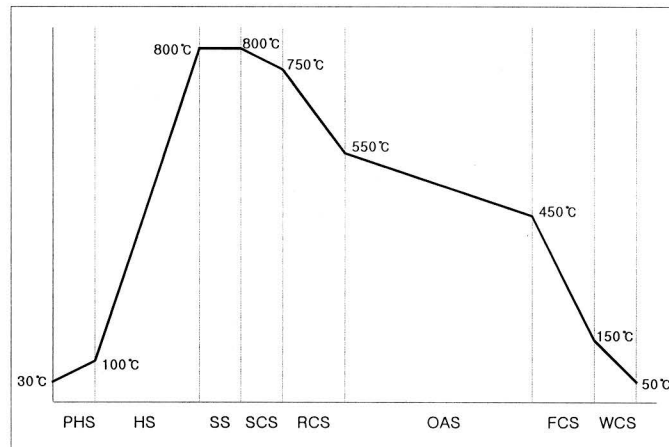


Fig. 2. Typical temperature distribution of a CAL

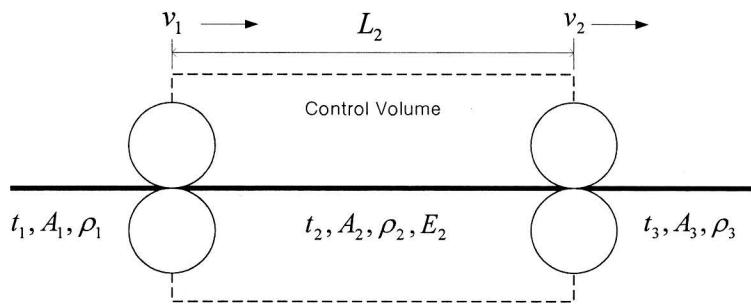


Fig. 3. A one-span web transport system

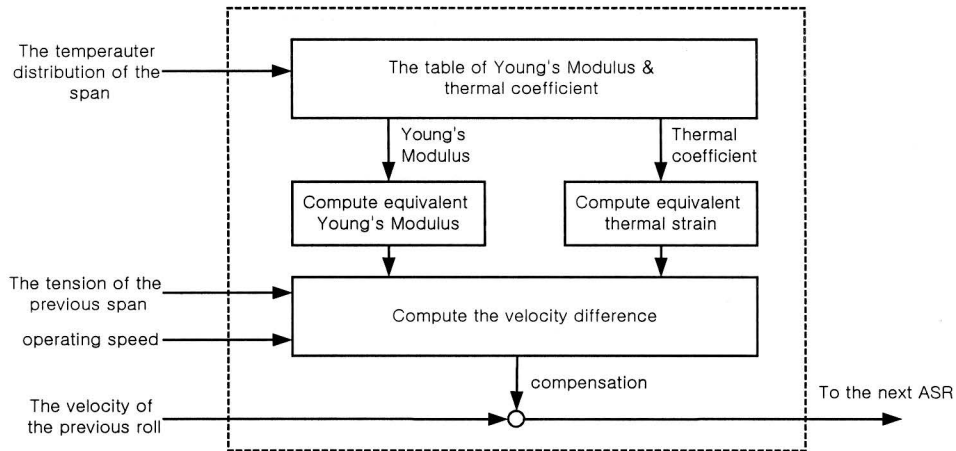


Fig. 7. The structure of the velocity compensator

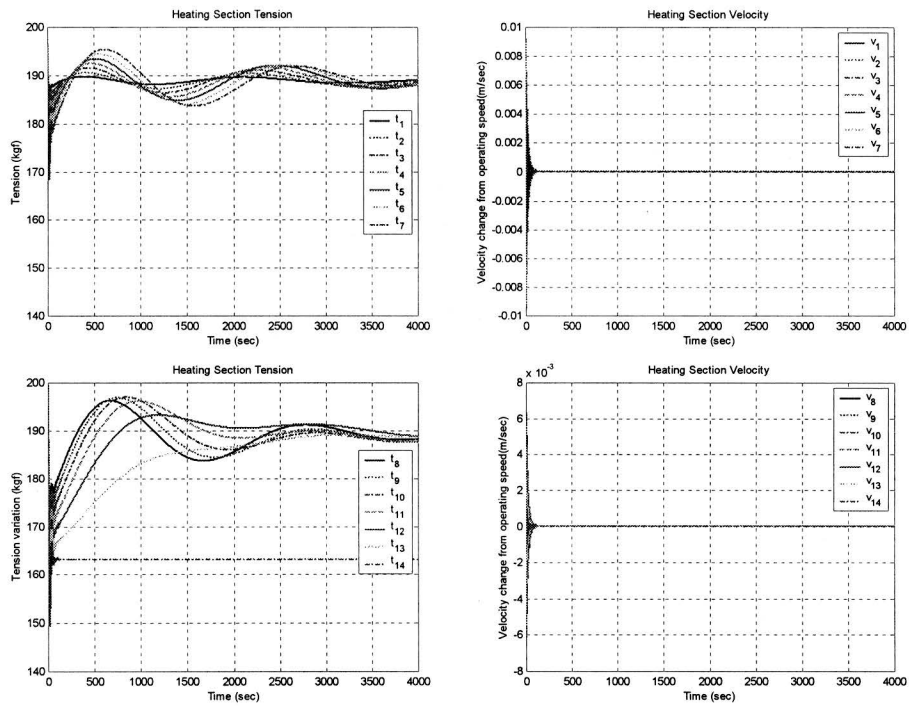


Fig. 8. The tension and the velocity in heating section with conventional control scheme (no temperature change)

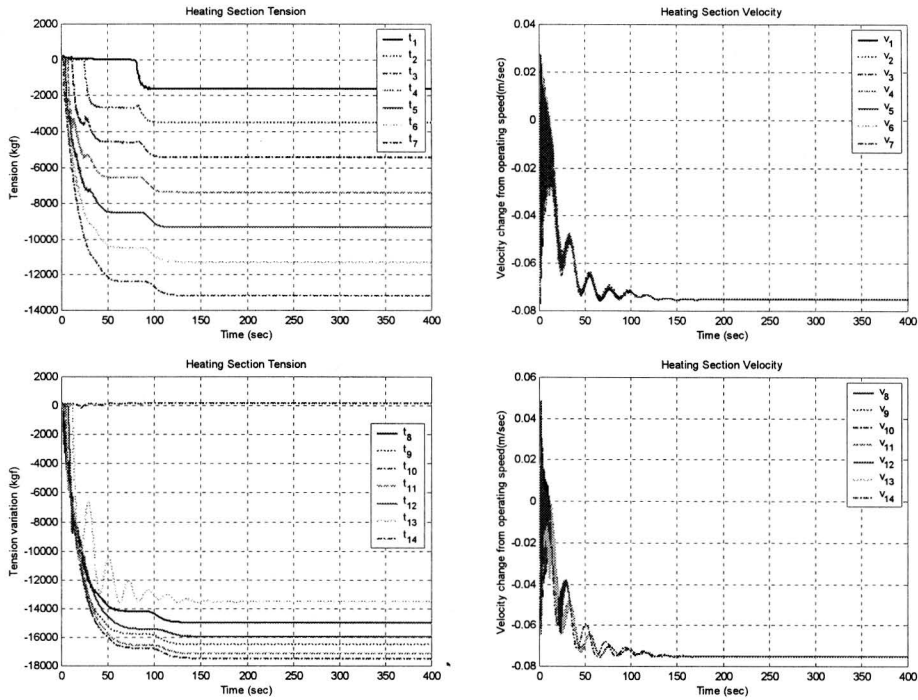


Fig. 9. The tension and the velocity in heating section with conventional control scheme

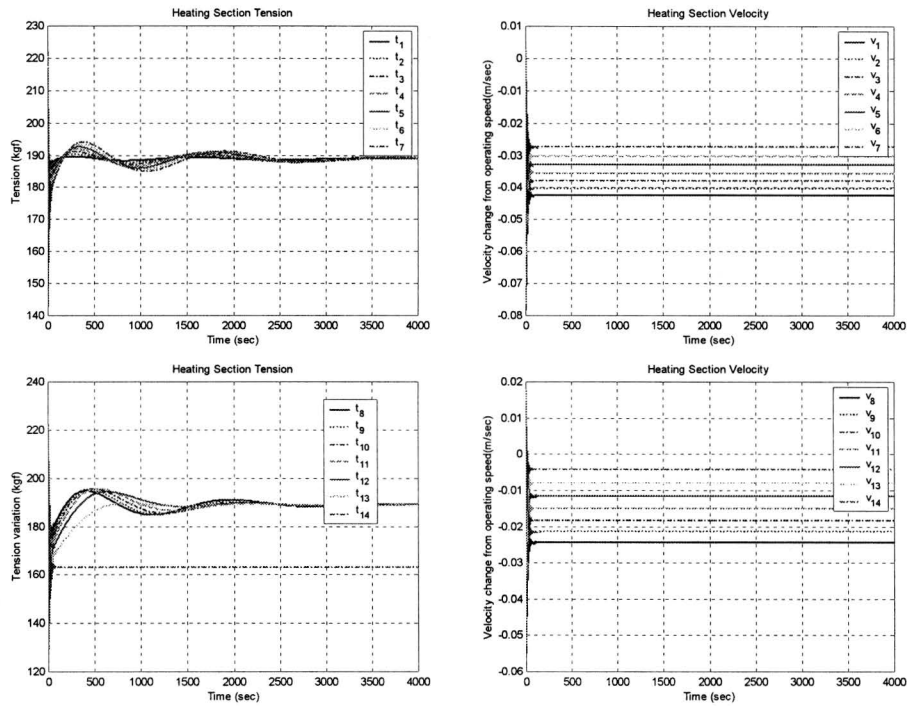


Fig. 10. The tension and the velocity in heating section with proposed control scheme

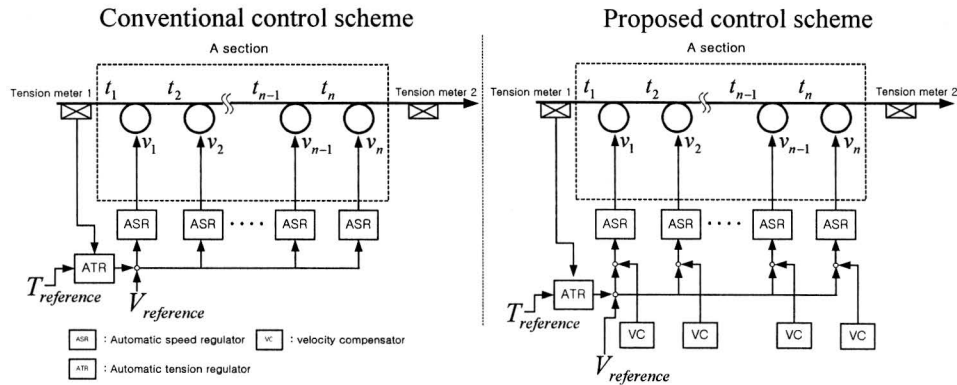


Fig. 11. Conventional control scheme VS proposed control scheme (final cooling section)

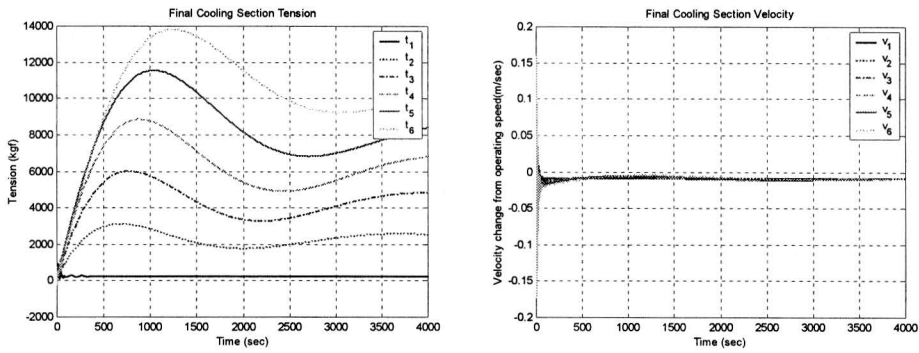


Fig. 12. The tension and the velocity in final cooling section (conventional control scheme)

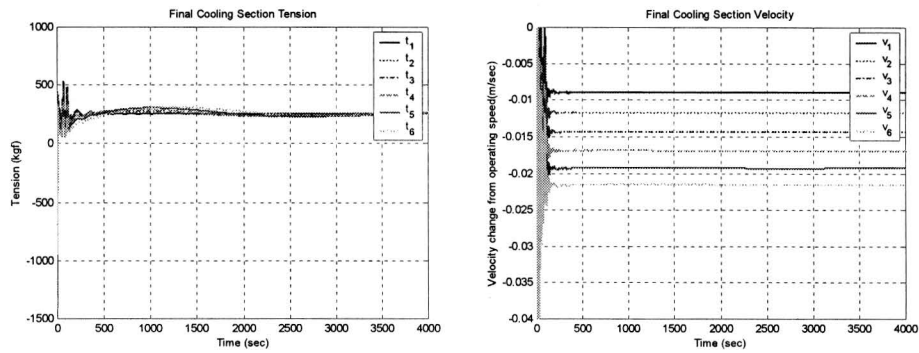


Fig. 13. The tension and the velocity in final cooling section (proposed control scheme)

Strip Tension Control Considering the Thermal Strain In Multi-Span Systems with Temperature Change **K. Shin, J. Jang, and K. Kim** – Kon-Kuk University, Korea

Name & Affiliation	Question
D. Hristopulous – Paprican	Would you elaborate on your assumption of ignoring changes in the cross section?
Name & Affiliation	Answer
K. Shin – KonKuk University	Usually within the furnace there are no big changes in cross sectional area. In the simulation I used the following data: the web thickness is 0.4 mm and the width is 700 mm. I do not believe it affect the result much even if there were minor changes in the cross section.
Name & Affiliation	Question
P. Pagilla – OSU	If all these spans are within the oven, if you assume steady state operation, and if you assume that the temperature is constant in the oven, I would expect a bias from the elastic tension. Where is the tension variation due to thermal strain? Is the thermal strain is not changing? What is $E_{\theta 1}$ in your paper? I believe Brandenburg may have included thermal aspects into his tension model in his 1997 paper, but I did not see that in your references.
Name & Affiliation	Answer
K. Shin – KonKuk University	Without changing the velocity at the ends of one span you can still have change in strain due to the thermal effect. It may result in droop of the web sometimes. Thus it is possible to have a strain change without having additional stress result at the ends of a span. The last term in the new tension model reflects the thermal effects on tension. Second question, $E_{\theta 1}$ is the youngs modulus of web at the outside of the furnace which is constant. For the third question, yes, Brandenburg considered the thermal effect. But, I introduced the concept of equivalent strain and Young's modulus to reflect the thermal effect. Yes, Brandenburg should have been added in my references.
Name & Affiliation	Question
P. R. Pagilla – OSU	The equation that you presented is the span before the oven and the span just within the oven. So if you consider two spans within the oven, do you see variations due to thermal strain? Because you are assuming that in steady state the temperature is constant.

Name & Affiliation	Answer
K. Shin – KonKuk University	My model considers the web both inside and outside of the oven. The temperature is constant at one point of a span, but not the same along the web within the span. Thus, even within a span, the thermal strain should be summed up and the Young's modulus needs to be changed accordingly as a function of temperature.