Behavior of Free Water under Centrifugal Fields

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遠心力場下의 自由水의 擧動

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ABSTRACT

본 연구는 목재중의 수분량이 변화하는 非定常狀態下에 있어서의 액체투과성을 평가하기 위한 새로운 방법으로써 遠心法에 의한 液體透過性의 평가법을 확립해 보고자 실시하였다. 이 방법은 遠心力場에 있어서의 脫水擧動과 遠心處理後의 飽水率로부터 液體透過性을 평가하는 것이다. 실험결과, 삼나무(*Cryptomeria japonica*)와 미송(*Pseudotsuga menziesii*)은 서로 다른 탈수경과를 나타내었다. 삼나무는 미송보다 더 많은 脫水量을 보였고 材內의 脫水量의 변이가 심하였다. 한편, 邊材와 心材의 脫水擧動에 있어서 삼나무는 氣體透過性에 의해 평가된 값과 상반된 결과를 나타내었다. 즉, 2200～3300rpm의 범위에서 邊材는 心材보다 탈수량이 적었다.

1. Introduction

Permeability is one of the most important factors in the fields of wood drying, wood preservation and chemical treatment, because such processing is always accompanied by the mass transfer of water or chemicals. As permeability closely relates to wood structure, there have been many studies to estimate a permeability from not only a practical aspect but also an anatomical aspect. To study the permeability of wood, we must consider the moisture condition of wood, that is wet or dry, and the change of mass fluid in wood that is in a steady or unsteady-state of mass.

Permeability can be determined by measurements using liquids (Hayashi et al. 1966) and gases (Sebastian et al. 1965; Matsumura 1995 a, b). However, these data may not provide relevant information for the field of wood drying because dried woods were used. In the case of dried wood, there is a possibility that the condition of pits changes during drying and a change in the size of the passageways is resulted from the drying process.

There are a few studies evaluating the liquid flow through wood in never-dried conditions (Comstock 1965; Ohgoshi et al. 1976, 1982). They measured the steady flow under the constant pressure differential. The measurement of the steady flow is useful in elucidating the factors affecting permeability. However, the data from this method may not often coincide with the unsteady flow accompanied by a change of water volume in wood because only the permeable factor is emphasized in the steady flow. It may be more important to understand unsteady flow than steady flow in practical wood processing, because the processings such as wood drying and preservation are always carried out under an unsteady-state.

I, therefore, have tried to develop a new approach, called the centrifugal method, to evaluate a permeability of never-dried wood under an unsteady-state. This method is designed to estimate water permeability from the behavior of dehydration under various centrifugal fields and the water saturation ratio after centrifugal treatment.

The centrifugal method was originally developed by Hassler and Brunner (1945) for the determination of the capillary pressure in small consolidated core samples. Choong and Tesoro (1989) measured ultimate moisture content at varied centrifugal forces using a short and longitudinal specimen and reported that the capillary pressure on the moisture content curve is dependent on the permeability characteristics of wood. Park et al. (1999) estimated the size distribution of free water paths in the undried heartwood of softwoods using the centrifugal method.

I investigated the behavior of dehydration under an unsteady-state and clarified the features within and between species, and between sapwood and heartwood.

2. Materials and Methods

2. 1. Centrifugal method

The method is based on the concept that water movement occurs by the balance of centrifugal force and water potential by meniscus (Park et al. 1999). Water stops where the pressure differential is zero. In the centrifugal field, only two factors affect water movement in wood, that is, centrifugal force and water potential by meniscus.

Centrifugal force (Ψ_f), which is independent of wood structure and is determined only by experimental conditions, is calculated from Eq. (1).

$$\Psi_f = \frac{\rho_w}{2} l_m (2\gamma_o - l_m)\omega^2 \qquad (1)$$

where Ψ_f is the centrifugal force per unit area (Pa), γ_o is the distance from the rotational center to the dehydrated surface (m), l_m is the arbitrary distance inward from the dehydrated surface (m) and ω is the angular velocity (S^{-1}, 2n, n : revolution per second).

Capillary pressure (Ψ_c), which is the pressure decreased by the curved surface of an air-water meniscus in wood, is calculated from Eq. (2).

$$\Psi_c = -\frac{2\rho\cos\theta}{r} \qquad (2)$$

where Ψ_c is the capillary pressure (Pa), γ is the surface tension of water (N/m), θ is the contact angle, and r is the radius of the capillary (m). Here, minus means the pressure in the water is lower than the pressure at the reference point. The reference point is the dehydrated surface in this case. The absolute value of Ψ_c shows the pressure differential between the water and ambient pressure.

If the water in the wood specimen is continuous, Ψ_f becomes large toward the rotational center. When Ψ_f becomes larger than the absolute value of Ψ_c, free water moves from the original site toward the dehydrated surface. When Ψ_f is equal to that of Ψ_c in wood, the movement of free water stops. As the water saturation ratio after dehydration shows the degree of water movement, it can be considered to indicate permeability.

2.2 Specimens

Two green logs each of Sugi (*Cryptomeria japonica*) and Douglas fir (*Pseudotsuga menziesii*) were used for this study. Logs were cut into 20cm-long-disks in order to prepared four end-matched specimens of 5cm in length. Disks were split into several sticks with about $2 \times 2\text{cm}^2$ in cross section and 20cm in length. Each stick, then, was divided into two 10cm-long sticks. The sticks were taken from sapwood and heartwood respectively. All the sticks were saturated by immersion in distilled water under alternating vacuum and atmospheric pressure with aspirator. They were immersed in distilled water for more than a week to ensure true saturation. After water saturation treatment was completed, each stick was divided into two 5cm-long specimens. After centrifugal treatment, each stick was cross-cut into five sections. The locations were two 5mm away from each end surface, and the rest were 10mm away from the cross cut surface, respectively.

2.3 Experimental procedure

Sakuma M160-IV was used as the centrifugal apparatus for this study. Four samples were dehydrated at the same time. Each sample was put in individual sample holders and placed in a well-balanced case. Because there were many small holes in the bottom of the sample holders, the water dehydrated from samples could be well drained through the holes. The specimens had no contact with the removed water. The distance from the rotational center to the dehydrated surface was 9.7cm. The rotational speed was selected at 5 level of 2200, 3000, 3300, 4800 and 6900rpm. End-matched specimens were allocated to 5 levels of different rotational speed. The ambient temperature during the centrifugal treatment was maintained at 10℃.

Four specimens were simultaneously treated for each run. Free water was dehydrated in the longitudinal direction. The treatment time of dehydration by centrifugation was determined as the time until the weight of each specimen become constant. The dehydration ratio of Sugi became nearly constant after 1 h, but Douglas fir did not show constant values even after 5 hours. However, the treatment was stopped after 5 h. After treatment, the specimens were divided into 6 longitudinal section (four sections of 1cm thick and both end section of 0.5cm) at the lines drawn before. Each section was weighed immediately and then was resaturated to obtain the maximum moisture content, mmax. After resaturation, it was oven-dried at 103 ± 2℃.

2.4 Water saturation ratio, SR

The water saturation ratio of a section was as follows;

$$SR = \frac{\text{Liquid Volume}}{\text{Void Volume}} = \frac{m_i - FSP}{m_{i\,max}} = \frac{\frac{W_i - W_{io}}{W_{io}} \times 100 - 28}{\frac{W_{imax} - W_{io}}{W_{io}} \times 100 - 28} \qquad (3)$$

where W_{imax}, W_i and W_{io} are the weight of a small section at water saturation, after centrifugal treatment and oven dried. In this study, the value of 28% was used for fiber saturation point (FSP).

3. Results and Discussion

Figure 1 shows the process curves of *SR* for heartwood of Sugi and Douglas fir. Sugi was dehydrated more than Douglas fir for all rotational speeds. The difference in the amount of dehydration under the centrifugal field indicates the difference of water permeability in an unsteady-state. The decrease of the *SR* of Sugi almost stopped after 3 hours for all conditions of rotational speed, but that of Douglas fir did not stop decreasing even after 5 hours. Sugi was 100% *SR* before the treatment, whereas Douglas fir did not reach 100% *SR*.

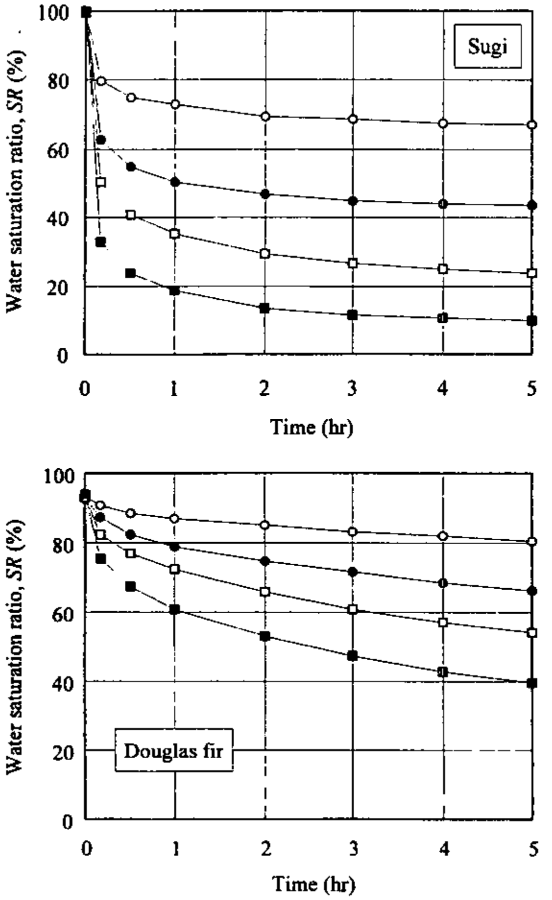

Fig 1. The process curves of the water saturation ratio of Sugi and Douglas fir heartwood for various conditions of rotational speed. Open circles: 2200rpm, Filled circles: 3300rpm, Open squares: 4800rpm, Filled squares: 6900rpm.

When the applied centrifugal force is equal to capillary tension (water potential) produced at the meniscus in wood, the movement of free water stops and the water saturation ratio (SR) reached theoretically maintains a constant value. However neither sapwood or heartwood of Douglas fir showed constant values and continued slight dehydration up to 5 hours under all centrifugal fields. The reason for this phenomenon may be presence of gas bubbles in the saturated water and wettability. Low wettability means air bubbles form easily at the boundary of wood and water. If a specimen with air bubbles in the cells is put under a centrifugal field, the air bubbles easily become large because of water potential.

Figure 2 shows the relationship between the *SR* reached after 5 hours and the rotational speed. The *SR* decreased with the increment of rotational speed. The decrease rate of the *SR* reached by the rotational speed depended on the species and the rate for Sugi was greater than that for Douglas fir.

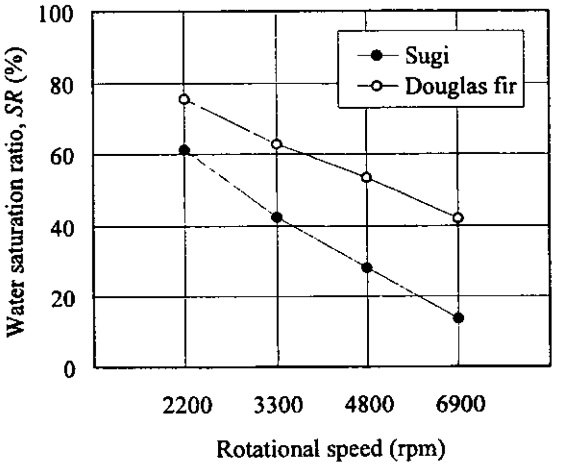

Fig 2. Relationship between the water saturation, *SR*, reached 5 hours, and the rotational speed in Sugi and Douglas fir heartwood.

Figure 3 shows the behavior of dehydration for Sugi. The dehydration of heartwood was easier than that of sapwood under centrifugal fields of 2200 and 3300rpm. Whereas the contrary result appeared at 4800 and 6900rpm. That is, free water in sapwood was dehydrated slightly more than that

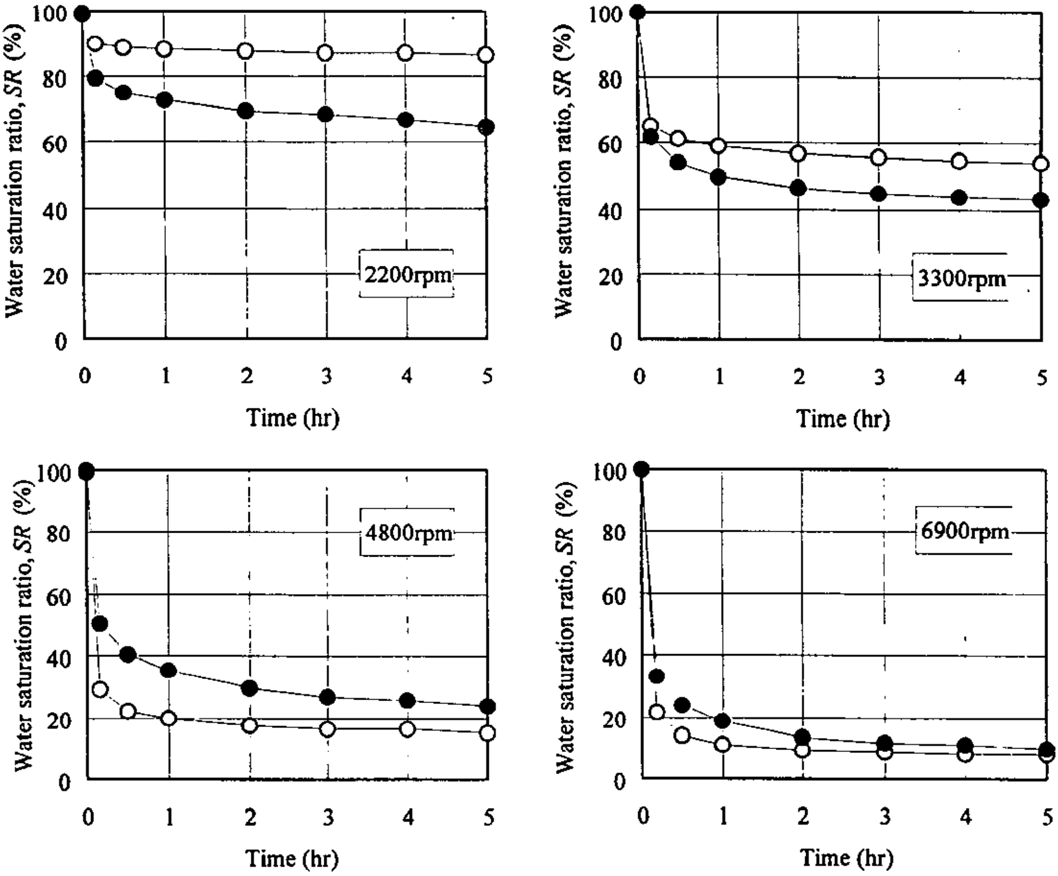

Fig 3. The process curves of the water saturation ratio, *SR*, between sapwood and heartwood of Sugi under various rotational speeds. Open circles: sapwood, Filled circles: heartwood.

in heartwood. Moreover, it was clear that the decreasing rate of *SR* in sapwood become near zero faster than that in heartwood.

Figure 4 shows the behavior of dehydration for sapwood and heartwood of Douglas fir. Douglas fir showed quite different patterns compared with Sugi. Sapwood was more permeable than heartwood for all of the centrifugal field. The decrease rate did not reach zero in 5 hours for both sapwood and heartwood.

Sapwood is known to be much more permeable than heartwood (Wardrop and Davies 1961; Comstock 1965; Hayashi et al. 1966; Erickson 1970). However, the water permeability in Sugi sapwood under an unsteady flow, centrifugal fields, was estimated to be lower than that in heartwood when the rotational speed was 2200 and 3300rpm.

The bordered pits are aspirated by capillary tension developed during drying or heartwood formation (Phillips 1933; Hart and Thomas 1967; Comstock and Côté 1968). It can be explained that the pit membranes in sapwood are moved from a central part in the pit chamber toward the pit border by applied centrifugal force and then the water movement is obstacled.

The water permeability in sapwood became

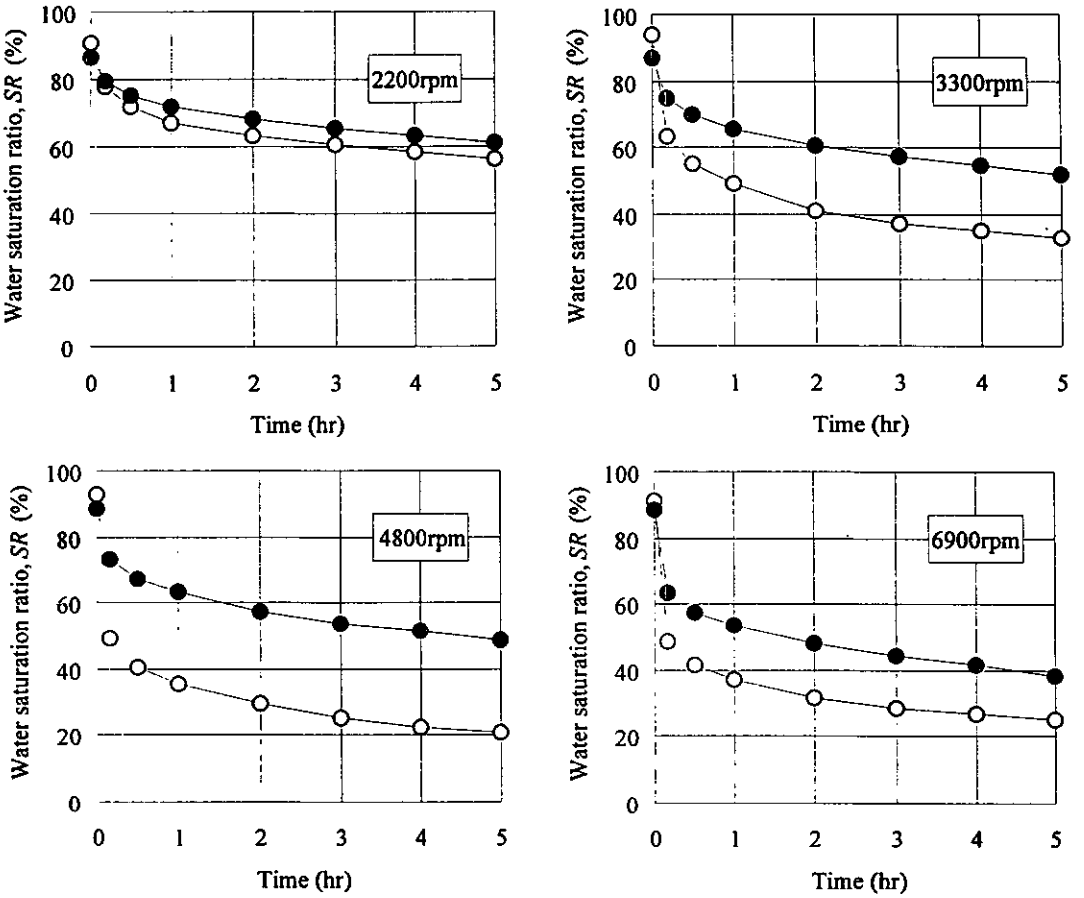

Fig 4. The process curves of the water saturation ratio, *SR*, between sapwood and heartwood of Douglas fir under various rotational speeds. Open circles: sapwood, Filled circles: heartwood.

slightly more permeable than that in heartwood under the elevated rotational speed of 4800 and 6900rpm. In regard to this phenomenon, I suggest that the pit membrane is ruptured by water potential developed at the meniscus with a small radius.

Figure 5 shows the scattering of water permeability within trees for heartwood of Sugi and Douglas fir. This data was obtained under the rotational speed of 3000rpm and each value was an average of 8 specimens. As shown in Figure 5, Sugi and Douglas fir showed the different process of unsteady flow under the same centrifugal field. Although scattering within trees existed in both species, Douglas fir showed a less scattering than Sugi in both tangential and radial directions. This indicates that Sugi has a large variation of liquid permeability in the wood.

Figure 6 shows the distribution of the *SR* reached after 5 hours. Sections with small numbers near the rotational center, always had a lower *SR* than those with large numbers. This means that the closer a position gets to the rotational center, the lower the *SR* becomes. This tendency coincides with the centrifugal force as shown in Eq. (1). However, the shapes of the curves are different. The *SR* of end-sections No. 1 and 6 were not measured, because they contained many incomplete tracheids.

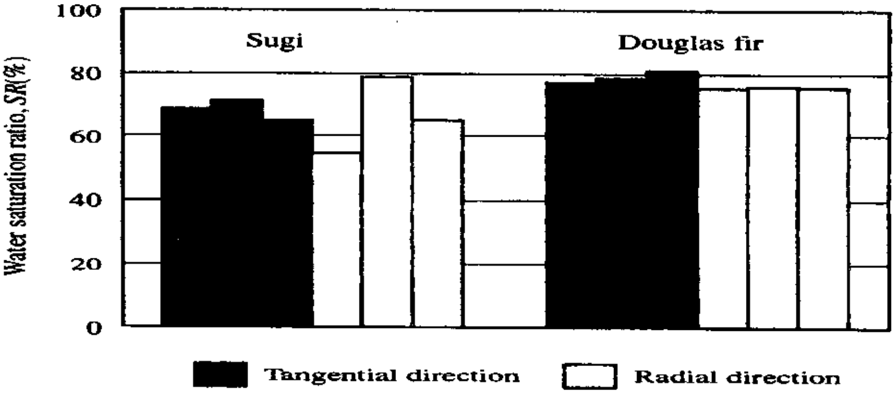

Figure 5. The *SR* within logs of Sugi and Douglas fir under a constant centrifugal field. Rotational speed: 3000rpm, Rotational radius: 9.7cm. Each value is an average of 8 specimens.

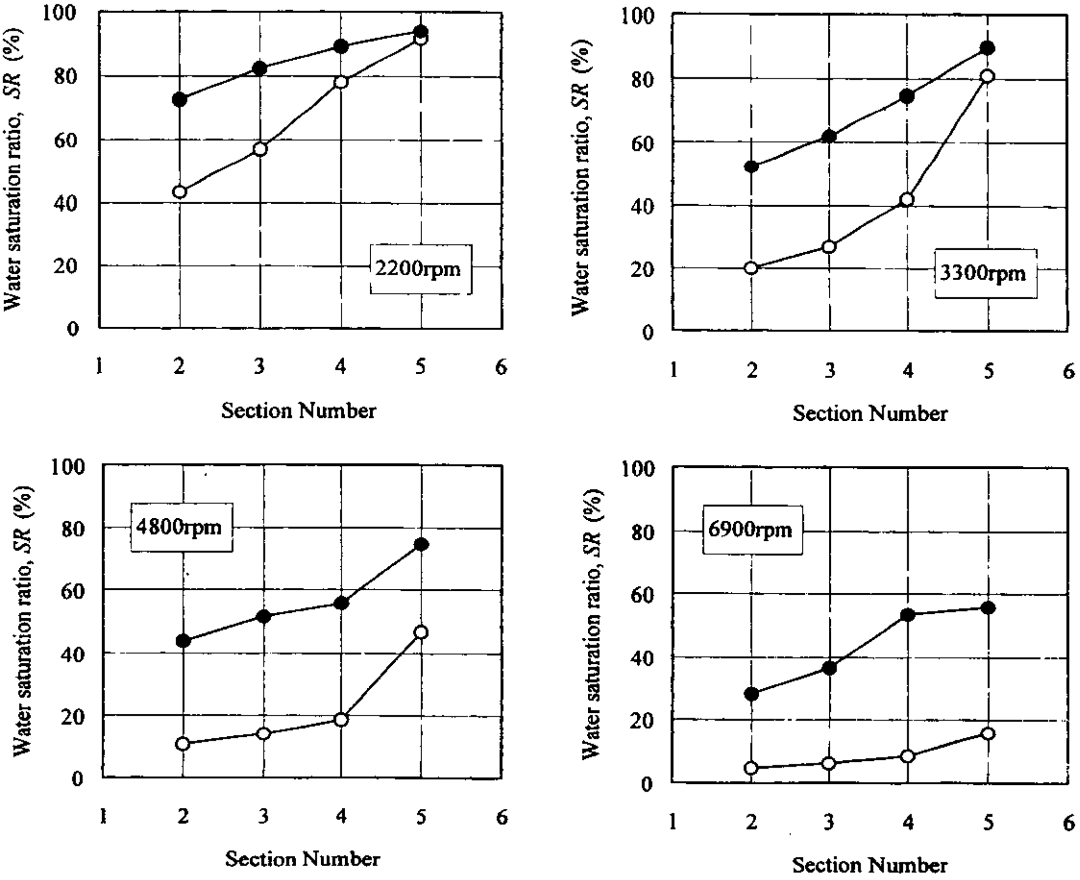

Fig 6. The distribution of the water saturation ratio, SR, for each section under centrifugal fields. The small number represents the section near the center of rotation. Open circles: Sugi, Filled circles: Douglas fir.

Conclusions

In this study, I tried a new approach to evaluate the water permeability of never-dried wood from the behavior of dehydration in the unsteady-state by the applied centrifugal fields. In comparison with conventional methods under the steady-state, this method estimates the behavior of free water in wood. Using this method, I have obtained the following results;

1) The behavior of dehydration under centrifugal fields depended on the species and Sugi had a larger permeability than Douglas fir.
2) The scattering of water permeability under centrifugal fields differed according to position of trees. The scatting of permeability in Douglas fir was lower than that in Sugi in both tangential and radial directions.
3) In the case of Sugi, the difference of water permeability between sapwood and heartwood showed different results estimated through gas permeability.

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