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Capillary Flow in Different Cells of *Thuja orientalis, Gmelina arborea, Phellodendron amurense*

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Abstract: A study was carried out to observe the 1% aqueous safranine solution flow speed in longitudinal and radial directions of softwood *Thuja orientalis* L., diffuse-porous wood *Gmelina arborea* Roxb., and ring-porous wood *Phellodendron amurense* Rupr., Longitudinal flow was considered from bottom to top while the radial flow was considered from bark to pith directions. In radial direction, ray cells and in longitudinal direction tracheids, vessel and wood fiber were considered for the measurement of liquid penetration speed at less than 12% moisture contents(MC). The variation of penetration speed for different species was observed and the reasons behind for this variation were explored. The highest radial penetration depth was found in ray parenchyma of *T. orientalis* but the lowest one was found in ray parenchyma of *P. amurense*. The average liquid penetration depth in longitudinal trachied of *T. orientalis* was found the highest among all the other cells. The penetration depth in fiber of *G. arborea* was found the lowest among the other longitudinal cells. It was found that cell dimension and also meniscus angle of safranine solution with cell walls were the prime factors for the variation of liquid flow speed in wood. Vessel was found to facilitate prime role in longitudinal penetration for hardwood species. The penetration depth in vessel of *G. arborea* was found highest among all vessels. Anatomical features like ray parenchyma cell length and diameter, end-wall pits number were found also responsible fluid flow differences. Initially liquid penetration speed was high and the nit gradually decreased in an uneven rate. Liquid flow was captured via video and the penetration depths in those cells were measured. It was found that even in presence of abundant rays in hardwood species, penetration depth of liquid in radial direction of softwood species was found high. Herein the ray length, lumen area, end wall pit diameter determined the radial permeability. On the other hand, vessel and fiber structure affected the longitudinal flow of liquids. Following a go-stop-go cycle, the penetration speed of a liquid decreased over time.

Keywords: *Cappillary flow rate, Thuja orientalis, Gmelina arborea, Phellodendron amurense Tracheids, Vessel, Wood fiber, Ray prenchyma*

1. Introduction

As the structure of vessels and tracheid facilitates longitudinal liquid flow in living trees, it is not surprising that vessels and tracheid play a primary role in liquid penetrability. Nonetheless, their effectiveness is dependent upon size, number, and distribution, and even more importantly upon the extent of extraneous materials and tyloses present, as well as upon the character of pitting that leads to contiguous cells. The factors emphasized in the present study are vessel anatomical features, fiber and ray parenchyma related to liquid permeability. Liquid flow within wood is controlled by the continuity of the porous structure of wood.

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Hardwoods, owing to large variety of tissue types, are more complex than that of softwoods. The variation in size and distribution pattern of structural tissues is considered to be the main cause of variation in flow/penetration patterns, even within a species.

In coniferous wood, the tracheids are imperforate, so there is general agreement that the principal longitudinal flow path is from tracheid to tracheid through bordered pit pairs (Siau 1984; Flynn 1995). Tangential fluid flow is also primarily through longitudinal tracheids and bordered pits between them (Erickson 1970; Keith and Chauret 1988). Air permeability measurements indicate that the total number of micro pores involved in tangential flow is approximately 103 times less than the number for longitudinal flow (Petty 1970; Flynn 1995). But the longitudinal flow is dependent upon the capillary structure of longitudinal tracheid and pit structure. Ray parenchyma and ray tracheids help in lateral conduction. The penetrated liquid can diffuse to the adjacent tracheids through cross field pitting (Olsson *et al.* 2001). The distance penetrated by liquids, however, varied from species to species, because of ray arrangement. Lateral transport of fluids in the wood structure is accomplished mainly through the ray cells which are radially oriented. They are connected to vessels via pits (vessel-ray pit) and thus help in radial conduction of liquid. As there is a large structural variety existed, the movement of liquid flow in wood is thus highly complicated.

According to Watanabe *et al.* (1998), there are 2 types of liquid movement in wood: diffusion through the cell wall sand flow in the cell lumens; the latter is considerably more prevalent during wood processing. The wetting rate via capillary action is much faster than via diffusion. In practice, to improve the rate of penetration and the maximum absorption of liquid sand solutions, the depth of capillary penetration is to be increased. Therefore, the present study aimed to observe free liquid soaking via capillary action only. This liquid flow not only depends on the moisture content of wood (Hansmann *et al.* 2002), but also on the principle direction of the grain (Bolton 1988; Fujii *et al.* 2001; Kamke and Lee 2007), as well as various physical, chemical (Hansmann *et al.* 2002), and anatomical characteristics (Thomas 1976; Owoyemi and Kayode 2008). Although fiber often constitutes the majority of woody tissue, general fiber is not considered as important as vessels in primary liquid flow (Leal *et al.* 2007). Nonetheless, fiber permeability may influence the subsequent spreading of liquid from vessels or other cells connecting them to pits. Compared to vessels, non-perforated fibers are thick walled and have relatively small pits that are not adapted for efficient liquid conduction. In addition, inter connecting pits provide one of them ain path ways for the flow of liquid between cells, and their structure and distribution affects the penetration of liquid in wood (Sano 2004). The air that is compressed during liquid penetration lowers the permeability of wood (Virta *et al.* 2006).

The present study was primarily concerned with finding an explanation for treatability differences in various cells and identifying the cause of that variability related to anatomical features. A considerable quantity of anatomical data are available for soft and hardwood species; however, only a limited number of attempts have been made to understand the behavior of liquid penetration related to anatomical structures. Therefore, this study is an effort to determine the anatomical features that affect

non-steady liquid (safranine solution) flow in radial and longitudinal directions. A crucial importance is in any explanation of treatability differences in different cells as well as with the difference in *Thuja orientalis* L., *Gmelina arborea* Roxb., *Phellodendron amurense* Rupr. and to find the reason for variability in accordance with anatomical features and properties of permeable liquids. There are only limited attempts to under stand the liquid penetration behavior in different cell type. Therefore, those important wood species is taken in account to find out the anatomical features and different liquids which affect the flow in radial and longitudinal directions.

2. Materials and Methods

2.1. Materials

This study was carried out in *Thuja orientalis* L., *Gmelina arborea* Roxb.. and *Phellodendron amurense* Rupr. for simplification they will be denoted by *T. orientalis,* and *P. amurense* respectively. Wood discs of two wood species were collected from non-leaning and defect free trees from dongsan-myen, chuncheon-si, Gangwondo, Republic of Korea. Discs were made from freshly cut log sat 1.2 above the ground level respectively. Discs of *Thuja orientalis* L. were made and marked to identify top and bottom end. Discs were kept in air tight cellophane bag to protect the moisture loss and brought to the laboratory. The discs of *G. arborea* was collected from wood identification laboratory of Kangwon national university.

Experiment condition is Humidity 50%, Temperature 24°C, no wind speed and Moisture content 10~12%. After green weight and dry weight measured, calculate on moisture content's formula.

2.2. Methods

2.2.1. Micro-structural measurement

Cross, radial and tangential micro-sections of 15-20 μm thickness were obtained by using a sliding microtome. Then they were double stained with safranine (Junsei Chemical Co., Ltd.) and light green solution, dehydrated in alcohol and mounted with Canada Balsam on glass slides. Macerating from sample strips (1 × 1 × 10 mm) using Schultz's solution for the measuring of vessel and fiber length, the length was measured by *i*-Camscope (mode lSV 32) equipped with an image processing software (Image and Microscope Technology, *i*-solution 2.5). Each micro-structural feature was measured from pith to bark. Radial, tangential and cross sectional blocks (3 mm × 3 mm) were finished with a microtome and the clean-cut surface was cut into 1mm thickness. After vacuum drying, the blocks were adhered to aluminums tubs with double-sided tape and coated with platinum (Pt) by using an ion sputter apparatus (HITACHIE-1010). At different resolutions and magnifications, the samples were examined at accelerating voltage of 5 kV in a Field Emission Scanning Electron Microscope. Because of the elliptical shape of intervesel pit aperture, fiber pit aperture and cross section of ray parenchyma, their perimeters were calculated for better explanation of the structural differences between two hardwood species.

2.2.2. Measurement of liquid penetration depth

Two 50 × 50 mm stakes were prepared from wood. Each stake was subdivided into 3 blocks (producing 6 blocks each 50 mm long). Outer two blocks were used for moisture content and specific gravity measurement while treatment samples were prepared from the middle block. The fiber saturation point (FSP) is a very im-

Table 1. Different Micro-structural Feature

Species	Anatomical properties	Mean	Min.	Max.
T.orientalis	Length of Longitudinal Tracheid (μm)	1,246.81 (± 308.30)		
	Length of Ray Parenchyma (μm)	333.93 (± 41.05)		
	Diameter of Latewood Longitudinal Tracheid Lumina (μm)		4.13 (± 0.30)	13.18 (± 1.27)
	Diameter of Earlwood Longitudinal Tracheid Lumina (μm)		6.79 (± 1.10)	20.10 (± 1.54)
	Diameter of Ray Parenchyma Lumina (μm)		4.21 (± 0.46)	12.42 (± 1.42)
	Area of Ray Parenchyma Lumina (μm^2)	41.14		
	Diameter of pit aperture in longitudinal Tracheid (μm)		3.62 (± 1.45)	4.48 (± 1.47)
	Area of pit aperture in longitudinal Tracheid (μm^2)	12.73		
	Diameter of Cross Field Pit Aperture (μm)		1.94 (± 1.01)	3.69 (± 1.23)
G.arborea	Length of Vessel (μm)	293.20 (± 35.55)		
	Length of Fiber (μm)	1,060.05 (± 197.20)		
	Length of Ray Parenchyma (μm)	69.18 (± 9.27)		
	Diameter of Vessel Lumina (μm)		80.26 (± 4.36)	157.47 (± 30.32)
	Diameter of Fiber Lumina (μm)		18.42 (± 2.49)	37.73 (± 6.76)
	Diameter of Ray Parenchyma Lumina (μm)		13.84 (± 1.59)	22.09 (± 2.42)
	Area of Ray Parenchyma Lumina (μm^2)	240.10		
	Diameter of Intervessel pit aperture (μm)		4.71 (± 1.11)	6.33 (± 1.27)
	Area of Intervessel pit aperture (μm^2)	23.50		
	Diameter of Fiber pit aperture (μm)		0.96 (± 0.56)	1.96 (± 0.88)
	Area of Fiber pit aperture	1.48		
	Diameter of Vessel-Ray pit aperture (μm)		3.93 (± 1.95)	5.08 (± 2.46)
	Area of Vessel-Ray pit aperture (μm^2)	15.71		
	Diameter of Endwall pit aperture in Procumbent Cell (μm)		4.85 (± 0.94)	6.50 (± 1.25)
	Numbers of Endwall pits of Procumbent Cell	13		
P.amurense	Length of Large Vessel (μm)	352.60 (± 63.85)		
	Length of Small Vessel (μm)	435.06 (± 128.79)		
	Length of Fiber (μm)	629.91 (± 76.69)		
	Length of Ray Parenchyma (μm)	76.43 (± 17.46)		
	Diameter of Large Vessel Lumina (μm)		132.71 (± 18.53)	258.51 (± 15.40)
	Diameter of Small Vessel Lumina (μm)		33.59 (± 4.15)	78.12 (± 10.13)
	Diameter of Fiber Lumina (μm)		10.59 (± 1.91)	31.02 (± 3.89)
	Diameter of Ray Parenchyma Lumina (μm)		2.76 (± 0.68)	8.52 (± 1.40)
	Area of Ray Parenchyma Lumina (μm^2)	18.46		
	Diameter of Intervessel pit aperuture (μm)		2.77 (± 1.66)	4.13 (± 1.58)
	Area of Intervessel pit aperuture (μm^2)	9.03		
	Diameter of Vessel-Ray pit aperture (μm)		0.81 (± 0.16)	1.12 (± 0.21)
	Area of Vessel-Ray pit aperture (μm^2)	0.72		
	Diameter of Endwall Pit Aperture in Procumbent Cell (μm)		0.85 (± 0.20)	0.96 (± 0.02)
	Numbers of Endwall pits in Procumbent Cell	34		

portant property and is assumed that the FSP is the moisture content below which the physical and mechanical properties of wood begin to change (Siau 1984). In this point, cell walls are saturated with bound water with no free water in cell cavities. As the average moisture contents is less than 12%, samples with this moisture level were considered for measuring liquid penetration depth by preparing 10 mm (T) × 2 mm (R) × 7 mm (L) for longitudinal and 7 mm (T) × 10 mm (R) × 2 mm (L) for radial samples. Treating samples were then sealed with silicon resin except one tangential and cross end for longitudinal penetration and one radial and tangential surface to observe radial penetration. Longitudinal penetration was observed in tangential surface as the vessel, tracheid or fiber is not interrupted with ray parenchyma. 1% safranine aqueous solution was allowed to penetrate from corresponding non-sealed end and the penetration was video captured by *i*-Camscope. With *i*-Solution software, liquid impregnation was video captured in audio video inter leave (avi) format for 5minutes. The captured video file was divided into specific frame sat 0.334, 0.667, 1.067 and 1.401 second for longitudinal and frame sat 0.334, 6.071, 11.741 and 17.412 second for radial direction by Vitrual Dub-MPEG 21.6.19 software. All samples were used in triplicate.

2.2.3. Statistical analysis

Liquid penetration depth was analyzed by using a one-way ANOVA. When significant differences occurred ($P \leq 0.05$), the EXCEL procedure was performed followed by a Duncan significant difference post hoc test to separate the cell effect on liquid penetration.

3. Results and Discussion

3.1. Anatomical characteristics of wood species

Different anatomical features like tracheid length, tracheid lumen diameter, ray cell lumen diameter, ray cell length, vessel lumen diameter, fiber length and lumen diameter, and vessel length affect the longitudinal and radial liquid flow of liquid (Ahmed and Chun 2009). So, different micro-anatomical measurements were performed for three wood species. Table 1 shows different micro measurements for *T. orientalis, G. arborea* and *P. amurense*.

The length, of the longitudinal tracheid, the vessel and the fiber was longest at the longitudinal tracheid of *T. orientalis* (1,246.81 μm), and the others were smaller than one of that, that was fiber (1,060.05 μm) in *G. arborea*, fiber (629.91 μm) in *P. amurense*, small vessel (435.06 μm) in *P. amurense*, large lessel (352.60 μm) in *P. amurense*, and small vessell (293.20 μm) in *G. arborea* respectively. The lumen diameter, of the longitudinal tracheid, the vessel and the fiber was smallest in the longitudinal tracheid of *T. orientalis*, and the ones of the others were of fiber in *P. amurense*. of fiber in *G. arborea*. of small vesse in *P. amurense*, of small vessel in *G. arborea*, and of large vessel in *P. amurense*, in ascending order of size respectively. Ray lumen area was found smaller in *P. amurense* (18.46 μm^2) than those in *G. arborea* (240.10 μm^2) and *T. orientalis* (41.14 μm^2). The length of ray parenchyma was longer in *T. orientalis* (333.93 μm) than those in *P. amurense* (76.43 μm) and *G. arborea* (69.18 μm). The numbers of endwall pits of procumbent cell were 13 in *G. arborea*, and 34 in *P. amurense*. The diameter of procumbent endwall pits in *G. arborea*, was larger than the one of *P. amurense*. The area of the intervessel pit aperture in *G. arborea*.(23.50 μm^2) was the

largest, and the smallest one was of the intervessel pit in *P. amurense* (9.03 μm^2).

The diameter of large vessel in *P. amurense* was 1.65 times wider than vessel of *G. arborea*. Length of fiber in *G. arborea* was 1.69 times longer than that *P. amurense*. Area of intervessel pit aperture was found 2.60 times wider on *G. arborea* thanthatin *P. amurense*. Area of vessel-ray pit aperture was found larger in *G. arborea* than that in *P. amurense.* On the contrary, different anatomical measurements for *T. orientalis* are presented in. The average tracheid diameter was found smaller than hardwood vessels. Longitudinal tracheid length was longer than vessel in *G. arborea* and *P. amurense*.

3.2. Penetration depth

The liquid flow through capillary structure of wood may be considered as comparable to the flow through glass capillaries in series. The flow rate in a capillary is the integral of the flow depth over the cross section. For a circular conduit, the flow rate of D can be expressed by Poiseuille's equation (Stamm and Raleigh 1967):

$$D = \frac{n\pi r^4 \Delta P}{8\eta L} \equiv \frac{qr^2 \Delta P}{8\eta L} \quad (1)$$

Where D is the volume of flow in cm^3/sec, r is the capillary radius, L is their length, q is the cross sectional area of the channel, ΔP is the pressure difference in dyne/cm^2, and in poise. According to equation (1), two capillaries with same length when one has a radius ten times than the other, the flow through the larger capillary would be 10,000 times more than that of small capillary under the same driving force. But if they are connected in series, then volume of liquid flow would be the same. When the individual wood cell as a single capillary conduit is compared, the liquid flow will follow the capillary equation mentioned below:

$$h = \frac{2\gamma Cos\theta}{\rho g r} \quad (2)$$

Where, h is penetration depth of liquid in capillary, radius is r, ρ is the density and γ surface tension of liquid which make a contact angle with capillary conduits with Θ and the acceleration of gravity is g. Based on this model, it is assumed that liquid will penetrate more in narrow capillary than that in wider one. Thus, the flow depth in wood capillary structure is directly related to capillary radius. Nevertheless, it is very difficult to implicate this phenomenon to wood composed of parallel capillaries with different radius. In addition, as penetration proceeds, the air present in the capillaries is compressed by advancing liquid, which gradually reduces the ΔP. The entrapped air needs to pass through any encountered constrictions (pits) for further liquid penetration. Therefore, pits are playing an important role for liquid conduction.

A study was carried out to observe the 1% aqueous safranine solution flow speed in longitudinal and radial directions of softwood *T. orientalis.*, diffuse-porous wood *G. arborea*, and ring-porous wood *P. amurense.* Longitudinal flow was considered from bottom to top while the radial flow was considered from bark to pith directions. In radial direction, ray cells and in longitudinal direction tracheids, vessel and wood fiber were considered for the measurement of liquid penetration speed at less than 12% moisture contents (MC). The variation of penetration speed for different species was observed and the reasons behind for this variation were explored.

The average liquid penetration depth in longitudinal trachied of *T. orientalis* was found the

highest among all the other cells. The penetration depth in fiber of *G. arborea* was found the lowest among the other longitudinal cells. It was found that cell dimension and also meniscus angle of safranine solution with cell walls were the prime factors for the variation of liquid flow speed in wood. Vessel was found to facilitate prime role in longitudinal penetration for hard wood species. The penetration depth in vessel of *G. arborea* was found highest among all vessels.

Anatomical features like ray parenchyma cell length and diameter, end-wall pits number were found also responsible fluid flow differences. Initially liquid penetration speed was high and then it gradually decreased in an uneven rate. Liquid flow was captured via video and the penetration depths in those cells were measured. It was found that even in presence of abundant rays in hardwood species, penetration depth of liquid in radial direction of softwood species was found high. Herein the ray length, lumen area, end wall pit diameter determined the radial permeability. On the other hand, vessel and fiber structure affected the longitudinal flow of liquids. Following a go-stop-go cycle, the penetration speed of a liquid decreased over time.

Vessels are connected end to end through perforation plate. The resulting vessel can be long and continuous (Thomas 1981). Various gummy, resinous and chalky exudates often form in vessel lumen with the heartwood and the formation of these materials substantially reduces the treatability of heartwood. So, in the same wood species, the penetration of liquid can be differed from above mentioned areas.

Longitudinal penetration is mainly conducted by vessel along with wood fiber. As vessel arrangement is more likely to be a hollow tube interconnecting with other vessel in end to end direction with perforation plates, liquid faces a less obstacle for flowing compare with wood fiber. So, longitudinal flow definitely will be related with vessel diameter. Fiber has non perforated end. Even though fiber structure does not facilitate the easy penetration of liquid, sometimes it conducted more liquids than vessels. Fibers constitute the bulk of woody tissues, in general they are not considered to be as important as vessels in initial liquid penetration. However, their permeability may have a decided influence on the subsequent spread of liquid from vessels. Compared to vessels, fibers with thick cell walls and irregular distribution of relatively small pits do not appear especially adapted for liquid conduction. Since liquid flows between fibers is depended primarily on pits and these structures were also examined. On the other hand, it is well known from Young-Laplace equation that the narrow cell lumen has higher capillary pressure than the wider one. So, cell diameter was also considered. These features are directly related with variation of longitudinal penetration. In radial penetration, the anatomical features found for the variation includes lumen diameter of ray parenchyma and length, end-wall pit number and diameter. So, the prime anatomical factors which could be responsible for the penetrability difference in vessel, fiber and ray are mentioned in Table 1.

Differences in permeability between longitudinal and transverse samples varied greatly depending on species and cells. This difference was prominent in longitudinal direction. There was striking difference in liquid penetration depth among softwood and hardwood species (Table 2 and 3). Especially the longitudinal tracheid was highly conductive. Liquid penetration depth in longitudinal tracheid of *G. arborea* ves-

Table 2. Longitudinal Capillary Flow Rate in Different Cells (μm)

Species	Cell	0.334 sec	0.667 sec	1.067 sec	1.401 sec
T. orientalis	Tracheid	262.94	430.92	621.95	774.69 (± 128.86)
G. arborea	Vessel	250.49	448.61	519.19	650.82 (± 189.48)
	Fiber	201.85	240.33	280.89	306.94 (± 74.51)
P. amurense	Large Vessel	228.67	340.06	414.53	571.92 (± 240.01)
	Small Vessel	275,57	372.74	491.99	577.55 (± 230.02)
	Fiber	158.70	284.02	336.52	381.98 (± 195.34)

Means with common letter in a given column are not significantly different at $P < 0.05$ level (Duncan Multiple Range Test)

Table 3. Ray Capillary Flow Rate in Different Species (μm)

Species	0.334 sec	6.071 sec	11.741 sec	17.412 sec
T. orientalis	58.31	222.89	360.84	403.84 (± 292.49)
G. arborea	72.17	119.22	142.92	163.91 (± 43.33)
P. amurense	99.22	132.14	140.44	156.48 (± 67.96)

Means with common letter in a given column are not significantly different at $P < 0.05$ level (Duncan Multiple Range Test)

sel was found 2.12 times higher than *G. arborea*. fiber respectively. Because of longer cell length and presence of highly porous pit membrane in bordered pit, the penetration depth in *T. orientalis* was thought to be higher than vessel or fiber in *G. arborea* and *P. amurense* Liquid penetration depth in fiber of *G. arborea* was higher than that of *P. amurense*. But vessel of *G. arborea* had higher penetration depth than large vessel of *P. amurense* and small vessel of *P. amurense*. This could be attributed to the cell arrangement of vessel and narrow diameter.

Tracheid of *T. orientalis* conducted the highest liquid penetration rate among three wood species. Fiber in *G. arborea* was more permeable than *P. amurense.* On the contrary, longitudinal tracheid of *T. orientalis* had almost as high penetration rate of large vessels in *P. amurense*. Due to longer cell length, longitudinal tracheid in *T. orientalis* had higher conduction rate than fibers in hardwood species. But this result was opposite than previous findings (Smith *et al.* 1996). The reason be hind for this experimental finding would be for considering the short period of time frame for liquid treatment.

Lumen diameter and length of ray can play an important role for the variability of penetration depth. It is reported that the capillary pressure is high in narrow cell lumen compared with wider one. If we compare the anatomical features of ray parenchyma, it will clarify the reason behind for the variation of liquid penetration. Shorter ray parenchyma with fewer end-wall pits could interrupt the liquid to flow without less resistance.

Ray cells are connected together end to end and form a capillary. Even the presence of capillary structure, Siau (1995) stated that for unknown reasons the conduction through hardwood ray tissues is not nearly as important despite the greater abundance of rays. This is because of the variation of ray cell structures. In softwood, the ray cells are long and have wider openings of end-wall pits (Ahmed *et al.* 2006). As a result, it played an important role in radial conduction of liquid compared with hardwood

rays. Studies have suggested that rays act as important flow paths for liquids during impregnation (Wardrop and Davies 1961; Banks 1970). Some authors have shown that the ray parenchyma in *T. orientalis* can act as important flow paths (Keith and Chauret 1988; Trenard and Gueneau 1984). The ray parenchyma, situated at the outermost tunnels in a ray, are often found to serve as an important liquid transport path during impregnation (Liese and Bauch 1967; Erickson and Balatinecz 1964).

In this experiment we explored the reason for lower conductivity of hardwood ray cells. Liquid passing through ray parenchyma is interrupted by end-wall. So, if the end-wall pit number is numerous with large diameter, the radial flow will be easier than those wood species with fewer end-wall pits with small openings. Not only end-wall pits but also numerous lateral-wall pits present in ray parenchyma through which liquid can pass to its neighboring ray cells, vessel or fiber. Arrangement of pitted ray cells facilitates the efficient liquid flow in radial direction. This is why the ray parenchyma plays an important role for lateral conduction. Even in same wood species the end-wall pit number and diameter, ray parenchyma diameter and length varied from juvenile to matured wood and early to latewood. Besides contact angle or meniscus angle is also responsible for liquid permeability in wood. Lower meniscus angle ($\Theta < 90°$) of liquid means the higher adhesion force with cell wall which leads that liquid to more contact with cell wall and ultimately rise capillary height. But the penetration speed is not only dependent on the surface tension of liquid but also the interaction with wood cell wall. The transformation from sapwood to heartwood causes changes in the parenchymatous cells. Polyphenols are laid down in the pits and in the walls of ray parenchyma (Bauch *et al.* 1974; Bamberand Fukazwa 1985) which should made heartwood ray parenchyma less permeable than that in sapwood. It was found that the average penetration depth in ray parenchyma of *G. arborea* was higher than those *T. orientalis* and *P. amurense*. As a result, ray parenchyma in *G. arborea* faces much more less obstacle in liquid flow compared with ray parenchyma those in *T. orientalis* and *P. amurense*. Table 2 and 3 depicts about the lateral flow depth in different cells of wood measured at different time. Ray parenchyma in *T. orientalis* had significantly 2.58 and 2.46 times higher penetration depth than that in *P. amurense* or *G. arborea* respectively. *G. arborea* ray parenchyma was found more permeable than *P. amurense* ray parenchyma.

The largest difference in permeability occurs between the longitudinal and transverse directions. Indeed, longitudinal flow is obviously much greater than transverse flow mainly because of high conductivity of vessels (Lihra *et al.* 2000). A significant difference of liquid flow depth was observed in ray parenchyma of two hardwood species. Radial flow occurs independently via the rays, the structure of the ray tissue and some other an atomical features may be the most important factors to dictate the permeability in this direction. Studies showed that pit membranes between parenchyma are thicker than intervessel pit membranes and fiber-fiber pit membranes, and consequently are less efficient for liquid path ways (Wheeler 1982).

4. Conclusions

Summary on the 1% aqueous safranine solution flow speed in longitudinal and radial directions of wood species should be provided (*T. orientalis.*, diffuse-porous wood *G. arborea*, and

ring-porous wood *P. amurense*,) The result was the followings;

1. The diameter of large vessel in *P. amurense* was 1.65 times wider than vessel of *G. arborea*.

2. The Length of fiber in *G. arborea* was 1.69 times longer than that *P. amurense*.

3. Area of intervessel pit aperture was found 2.60 times wider on *G. arborea* than that in *P. amurense*.

4. Area of vessel-ray pit aperture was found larger in *G. arborea* than that in *P. amurense.* On the contrary, different anatomical measurements for *T. orientalis* are presented in.

5. The average tracheid diameter was found smaller than hardwood vessels. Longitudinal tracheid length was longer than vessel in *G. arborea* and *P. amurense*.

6. The highest radial penetration depth was found in ray parenchyma of *T. orientalis* but the lowest one was found in ray parenchyma of *P. amurense.*

7. The average liquid penetration depth in longitudinal trachied of *T. orientalis* was found the highest among all the other cells.

8. The penetration depth in fiber of *G. arborea* was found the lowest among the other longitudinal cells.

9. As expected, following a go-stop-go cycle, the depth of penetration slowly decreased over time.

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