Drying on the board- and boxed heart squares-larch lumbers within an opaque solar drying house covered by a composite surface

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Abstract

Two sorts of lumber drying house covered by a composite surface consisting of three layer transparent films and a carbon-fibre sheet (CF-sheet; looks like a semi-opaque) were invented and developed. One of them was built in Ashoro-cho, the eastern part of Hokkaido, Japan (the first proving site), and the other was built in Asahikawa-shi, the central part of Hokkaido (the second proving site). The dimension of each drying houses is a frontage of 4.5 m, depth of 5.0 m and height of 3.4 m (the 1st site) and the same frontage and depth as the former, but height of 3.8 m (the 2nd site), respectively. Two types of models of the drying house (East-West type and South-North-type) were desinged. The former is shaped like a half Quonset hut and the latter a just Quonset hut. All of the surfaces including the roof and walls except for a north wall of both models are covered by a composite surface. The composite surface is specially consisted by a triple transparent film from upper side and a CF-sheet to bottom side between which there are a few space of air layers. As a result of mutual effect of a spectral radiation properties of the films and the CF-sheet, a total solar radiation incident upon the drying house with cubic body composed of multi-surface from all the sky globally, can be collected into the house as solar rays volumetrically, converted into infrared radiation and trapped inside the drying house as solar heat passively, without any electric power. Moreover, the moist air inside the house being evaporated when drying green lumber can be naturally exhausted through two insulated cylinders (chimney) outside the drying house according to a principle of the thermo-siphon. From these reasons, “An opaque solar lumber drying house covered by a composite surface consisting of a triple-transparent film and a CF-sheet” could be called “A fully passive solar lumber drying house” in other word.

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In this paper, after explained the principle of drying mechanism due to solar radiation and heat rays, the experimental procedures and the results at the proving test, on a board-larch lumber at the 1st proving site and a boxed heart squares-larch lumber for pillar material at the 2nd proving site, were described and discussed thoroughly. 

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Keywords: Triple transparent film; CF-sheet, Radiation property of composite surface, Fully passive drying house, Insulated cylinder, Transparent insulation/ blackbody cavity effect, Coefficient of (Iλ), Efficiency of volumetric solar heat collected, Energy balance, Wood drying.

1. Introduction

The subject to suppress the global warming and to decrease an exhaustion of carbon-dioxide is a heavy problem desired to solve without a delay, For this reason, it is mostly efficient to utilizes extensively a renewable energy such as solar energy, biomass energy and so on. For this purpose, due to collect solar energy effectively and convert into heat energy skilfully, first, an active-passive-type of a transparent house [1], next, a fully passive-type of a transparent house [2,3], and lastly a special opaque house to dry larch lumber [4,5,6] were discussed and designed seriously under a new concept as an example of green-house in the agriculture field. To exhaust passively the inner moist air containing water evaporated when drying green lumber, an insulated cylinder (Chimney) was stood on the outer side of the house. This principle of the new technology developed in this paper is needless any electric power for the collection of solar radiation and the exhaustion of moist air essentially. After a few steps of development of the technology, an experimental model named “Fully passive-type solar lumber drying house” from operational mechanism built in a rural field ultimately and it can be also called “An opaque solar lumber drying house covered by a composite surface” from outside view [7]. As specifics in this system, only a few hundred W of electric power needs for drive four small-fans to circulate inner air very slowly within the house and to drive feed pump for supplying hot water into a floor heater and two fan-convectors as the auxiliary heat sources. In summer, however, the larch lumber can be dried out nothing these auxiliary heats.

There are two types of an opaque solar lumber drying house covered by a composite surface which is called “solar drying house” in short; one of them is East-West type (EW type) and the other is South-North type (SN type) depend on an loading direction of packaged lumber rod in direction of east-west and south-north respectively. Where, specimen of lumber material is board-larch lumber (50 mm×100 mm×3.65 m) in the 1st proving site in Ashoro, and boxed heart squares-larch lumber (120 mm square×3.65 m) in the 2nd proving site in Asahikawa.

A principle when solar radiation incident upon the composite surface is collected, converted into infrared radiation and filled within the drying house as heat rays is due to radiation transmission, so that the drying process of larch lumber progresses efficiently and skilfully within the drying house filled with heat rays. In this case, to obtain the product with a much higher quality, the pre-steaming for the specimens on the boxed heart squares-larch lumber different from the board-larch lumber is needed.

In this paper, firstly, our concept of solar lumber drying method is explained theoretically, and then, the structure and dimension of the apparatus are subscribed, and lastly the drying performance and the experimental results are discussed. Where, the discussions on the results are mainly performed concerning an EW type of the model adopted in both sites Ashoro and Asahikawa.

- 2. Outline on the new concept
- 2.1. Principle of an operation of the drying house
An opaque house covered by a composite surface consisting with three transparent films [4], among which two air layers are contained and under which a carbon fibre sheet (CF-sheet) is spread with a few spaces, can transmit and absorb solar radiation (S. R.) incident upon the composite surface and convert it into solar heat, so that the inside of the house can be kept in high temperature due to trapped an infrared radiation inside the drying house efficiently (Fig.1). This phenomenon might be called “transparent insulation/blackbody cavity effect”, because a global S. R. incidence upon the volumetric house three-dimensionally (volumetric incidence), after converted into infrared radiation, is also absorbed three-dimensionally (volumetric absorption). This is a passive absorption or collection with nothing any electric power. While, two insulated cylinders are stood on the outside of the drying house and the moist air yielded when drying green lumber in the drying house can be exhausted through them owing to the suction force. This is because of the density difference between inside and outside airs due to temperature difference between them and that is called thermo-siphon phenomenon. This process is also done passively without any electric power. Since the absorption of both S. R. and exhaustion of moist air don’t depend on any motive power, this soft technology might be called “a fully passive solar lumber drying house”.

2.2. Mechanism of “the transparent insulation/blackbody cavity effect”

From Fig.1 [4], hence, if the transmittance of single sheet of transparent film $\tau_f$ is assumed 0.93, the relations and factors between the other radiation properties $\tau$, $\alpha$ and $\rho$ are as follows:

Transmittance of triple transparent film $\tau_T = 0.93^3 = 0.804$; Rate of solar ray passed through skeleton frame $\tau_F = 0.90$; Absorptance of CF-sheet $\alpha_{cf} = 0.70$; Transmittance of CF-sheet $\tau_{cf} = 0.15$; Reflectance of CF-sheet ($\rho_{cf}$) = 0.15, 

\[ \text{Transmittance-Absorptance of composite surface } (\tau, \alpha)_{cs} = \tau_F^3 \cdot \tau_T \cdot (\alpha_{cf} + \tau_{cf}) = 0.804 \cdot 0.90 \cdot (0.70 + 0.15) = 0.615 \equiv 0.6 \] (due to contamination loss of film).

Where, an apparent absorptance of CF-sheet $(\alpha_{cf} + \tau_{cf}) = (0.70 + 0.15) = 0.85$.

Therefore, a horizontal total S. R. $I_0(Tot)$ which is incident upon the drying house covered by a composite surface volumetrically is transmitted a triple transparent film and then is absorbed by CF-sheet spread underside that with few space and finally trapped into the house as solar heat, so that in this case, the efficiency of volumetric S. R. collected $\eta_{vc}$ is equal to a coefficient of transmittance-absorptance $(\tau, \alpha)_{cs}$. This efficiency of volumetric solar heat collected $\eta_{vc}$ is determined only by the spectral radiation
properties of the films and CF-sheet, and equals the \( (\tau,\alpha)_{CS} \) fixed always at 0.6 out of relation to the intensity and direction of S. R. incidence (Fig. 2). While an efficiency of S. R. collection of a usual flat-type solar collector is varied with intensity and the direction of S. R. incidence. Due to that, the maximum value of which reaches 0.6 instantaneously, however, the yearly averaged value is only 0.3 usually. A solar ray incident upon the composite surface which covers the opaque house is absorbed by CF-sheet, and then converted into solar heat (infrared radiation), therefore, the inside of the opaque house is filled with infrared radiation enough, so that it is kept a blackbody cavity with blackness 0.85 or more, because of that the infrared radiation inside the house is multi-reflected in cavity effect of the house, and moreover, is insulated by two air layers among three transparent films. Consequently, “transparent insulation/blackbody cavity effect” can be realized. As shown Fig. 2, an absorptance \( \alpha_{CF} = 0.7 \) and a transmittance \( \tau_{CF} \) of 0.15 of CF-sheet for incident ray, subsequently, the summation of them 0.85 corresponds to an apparent absorptance \( \alpha_{CS} \) of CF-sheet.

2.3. Calculation model and volumetric collection of a multi-flat surface house

Firstly, Table 1 indicates the intensity of S. R. incidence upon a tilt surface at the 1st proving site (Ashoro) from the database [12].

Table 1. Intensity of S. R. incident upon each surfaces of drying house at 1st proving Site; \( I(d)_{R/T} \) kWh/m²d (Ashoro; 43°14.5’N, 143°33.5’E)

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</tr>
</thead>
<tbody>
<tr>
<td>1) Roof surface;</td>
<td>0 =0°, a = 0°</td>
<td>1.88</td>
<td>2.82</td>
<td>3.85</td>
<td>4.43</td>
<td>4.93</td>
<td>4.96</td>
<td>4.41</td>
<td>3.84</td>
<td>3.27</td>
<td>2.73</td>
<td>1.86</td>
<td>1.54</td>
<td>3.38</td>
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<tr>
<td>( I(d)_{R/T} )</td>
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<tr>
<td>2) Roof surface;</td>
<td>0 =10°, a = 0°</td>
<td>2.37</td>
<td>3.33</td>
<td>4.27</td>
<td>4.54</td>
<td>5.01</td>
<td>4.98</td>
<td>4.44</td>
<td>3.94</td>
<td>3.48</td>
<td>3.10</td>
<td>2.27</td>
<td>1.97</td>
<td>3.65</td>
<td></td>
</tr>
<tr>
<td>( I(d)_{R/T} )</td>
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<tr>
<td>3) South wall;</td>
<td>0 =90°, a = 0°</td>
<td>3.74</td>
<td>4.40</td>
<td>3.94</td>
<td>2.87</td>
<td>2.48</td>
<td>2.31</td>
<td>2.21</td>
<td>2.22</td>
<td>2.48</td>
<td>3.12</td>
<td>3.03</td>
<td>3.10</td>
<td>2.99</td>
<td></td>
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<tr>
<td>( I(d)_{WS} )</td>
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</tr>
<tr>
<td>4) East and west</td>
<td>0 =90°, a = 90°</td>
<td>3.22</td>
<td>3.88</td>
<td>5.16</td>
<td>5.20</td>
<td>5.68</td>
<td>5.54</td>
<td>4.90</td>
<td>4.28</td>
<td>3.90</td>
<td>3.58</td>
<td>2.60</td>
<td>2.44</td>
<td>4.28</td>
<td></td>
</tr>
<tr>
<td>wall; ( I(d)_{WE/WW} )</td>
<td></td>
<td></td>
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</tbody>
</table>

From a figure of the house, because that a calculation on S. R. incident upon the circular surface is difficult, to simplifies the calculation, the curved roof surface is assumed as a flat surface, and the house is replaced with multi-surface consisting of flat surfaces, so that S. R. incidence upon each tilt surface \( I(d)_{tilt} \) kWh/m²d can be picked up from a database on Fig.1. After multiplying \( I(d)_{tilt} \) by each area of tilt surface, summing up them, the volumetric S. R. incidence can be obtained. Besides, to multiply them by a coefficient of transmittance-absorptance \( = 0.6 \), thus \( I(Q)_{VC} \) kWh/d can be calculated directly. This is called a conventional calculation method [2]. While, a normal calculation method [8] is fairly complicated, however, that is described simply as follows: a total S. R. incidence observed at the proving site, the tilt surface S. R. incidences per hour are calculated through a separation method of direct-scattered component, and after integrating them from sunrise to sunset hours and days, and summing up them during the period, thus we can calculated the volumetric S. R. incidence per period \( I(Q)_{VI} \). Now, an efficiency of volumetric solar heat collected \( \eta_{VC} \) is defined as Eq. (1):

\[
\eta_{VC} = I(Q)_{VI} \times (\tau,\alpha)_{CS} / I(Q)_{R} = \eta_{VI} \times (\tau,\alpha)_{CS}
\]

where, \( I(Q)_{R} \): S. R. incidence on a floor, \( \eta_{VI} \): Efficiency of volumetric S. R. incidence.
In Table 2, the experimental results of the main five times for EW type and SN type at the drying test period from Oct. 2006 to Aug. 2007 were shown selectively. The related matters on the drying test No. 3 on the EW type picked up from which will be explained under the following section: Fig. 3 shows a calculation model of an EW type of drying house provided for conventional calculation method. The house of EW type is formed a half Quonset hut, floor area of which is 22.5 m² (= 4.5 m×5.0 m), height is 3.4 m, and two insulated cylinders (height = 5.0 m, inside diameter = 300 mm) are stood up outside the house vertically. All surfaces of the house, except for north wall, are covered by a composite surface consisting of triple transparent film and CF-sheet, so the house looks like opaque from outside view.

Table 2. Number of the drying test and the result (Ashoro Site: Oct. 31, 2006 to Aug. 31, 2007)

<table>
<thead>
<tr>
<th>No. (Period of test)</th>
<th>Type</th>
<th>Outside</th>
<th>Inside</th>
<th>Total Heat, Eff. of Soar Heat</th>
<th>Volum Heat Collect.</th>
<th>Fract Solar Heat</th>
<th>Rate of Evaporation Heat %</th>
<th>Evaporation Water kg</th>
<th>Decrease in Moist. Content % (D.B)</th>
<th>Vol. of Stack Lumber m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1 (Oct.31- Nov.31/06)</td>
<td>EW</td>
<td>5.9/83.4</td>
<td>44.1/25.4</td>
<td>4368</td>
<td>148</td>
<td>711</td>
<td>16.3</td>
<td>13.0</td>
<td>978</td>
<td>34 to 6</td>
</tr>
<tr>
<td></td>
<td>SN</td>
<td>43.1/26.2</td>
<td>3810</td>
<td>121</td>
<td>637</td>
<td>167</td>
<td>11.3</td>
<td>753</td>
<td>32 to 7</td>
<td>8</td>
</tr>
<tr>
<td>No. 2 (Dec.13-Dec.28/06)</td>
<td>EW</td>
<td>-5.0/79.2</td>
<td>37.0/13.0</td>
<td>5619</td>
<td>161</td>
<td>850</td>
<td>16.4</td>
<td>11.2</td>
<td>1011</td>
<td>38 to 9</td>
</tr>
<tr>
<td></td>
<td>SN</td>
<td>36.7/13.0</td>
<td>5182</td>
<td>161</td>
<td>850</td>
<td>16.4</td>
<td>11.2</td>
<td>1011</td>
<td>38 to 9</td>
<td>8</td>
</tr>
<tr>
<td>No. 3 (Feb.19-Mat.4/07)</td>
<td>EW</td>
<td>-7.0/71.6</td>
<td>32.8/24.8</td>
<td>6040</td>
<td>173</td>
<td>1578</td>
<td>26.1</td>
<td>10.0</td>
<td>1052</td>
<td>39 to 6</td>
</tr>
<tr>
<td></td>
<td>SN</td>
<td>32.3/23.7</td>
<td>5090</td>
<td>140</td>
<td>1475</td>
<td>29.0</td>
<td>11.6</td>
<td>1055</td>
<td>39 to 9</td>
<td>8</td>
</tr>
<tr>
<td>No. 4 (May8-May22/07)</td>
<td>EW</td>
<td>101/65.9</td>
<td>36.1/27.1</td>
<td>3745</td>
<td>119</td>
<td>1464</td>
<td>39.1</td>
<td>20.6</td>
<td>1325</td>
<td>40 to 12</td>
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<tr>
<td></td>
<td>SN</td>
<td>36.3/30.0</td>
<td>3462</td>
<td>94</td>
<td>1325</td>
<td>38.3</td>
<td>22.3</td>
<td>1355</td>
<td>43 to 10</td>
<td>10</td>
</tr>
<tr>
<td>No. 5 (Aug.16-31/07)</td>
<td>EW</td>
<td>18.8/77.8</td>
<td>27.6/67.1</td>
<td>1813</td>
<td>126</td>
<td>1813</td>
<td>100</td>
<td>30.8</td>
<td>959</td>
<td>40 to 19</td>
</tr>
<tr>
<td></td>
<td>SN</td>
<td>27.7/64.1</td>
<td>1451</td>
<td>98.0</td>
<td>1451</td>
<td>100</td>
<td>40.9</td>
<td>1130</td>
<td>42 to 17</td>
<td>10</td>
</tr>
<tr>
<td>Average</td>
<td>4.5/75.6</td>
<td>35.4/31.5</td>
<td>4058</td>
<td>138</td>
<td>1233</td>
<td>30.40</td>
<td>18.20</td>
<td>1062</td>
<td>38.4 to 10.9</td>
<td>8.8</td>
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</table>

Fig. 3 Simple model of fully passive slar lumber drying house (East-West type)

North wall is made from insulated opaque wall and inside the house a packaged board-larch lumber of 10 m³ (max.) can be loaded in east west direction. Fig. 4 shows the state of loading of a packaged board-larch lumber (8.0 m³). Regarding an additional instruments in the EW type, in which a floor heater and two fan convectors (fan-con.) as auxiliary heats, besides four small fans to circulate the inside air slowly and forced out the moist air through two insulated cylinders are set up. Fig. 5 shows the calculated estimation on the performance factors of the EW type of the model.
The volumetric solar heat collected $Q_{VC}$, during from spring to early summer (March-June) is about 470 MJ/d largely. This value is corresponds to $\eta_{VC}$ equals 120 to 150 % which is a ratio to the S. R. incidence on the floor. As this, in general, the $\eta_{VC}$ is larger in winter and smaller in summer, and so the maximum of $\eta_{VC}$ is 205% in January, and consequently yearly averaged is 141 %. Fig. 6 shows hourly variation of the measurements inside and outside the drying house in detail: temperatures, humidity, total horizontal (floor area) S. R. incidence, and air velocity in the insulated cylinders and so on. Fig.7 [9,10] shows the drying speed on a board-larch lumber (50 mm × 100 mm × 3.65 m) at the 1st proving site. A capability of the drying house can be proved that green larch lumber of moisture content 40 % (dry base) was dried out under 10 % for fourteen days (e.g., Feb. 19 to Mar. 4/2007) even in winter to early spring season using an auxiliary heat, at which the S. R. dependence was 27.4 %. In midsummer, owing to only solar heat, the lumber drying from 40 % to 20 % or less during two weeks was possible, at which solar fraction was 100 % as a matter of course. In the Fig. 8, on the two types of the drying house, the efficiency of solar heat collected $\eta_{VC}$ was compared with the measured from the five proving tests (Oct. 31/’06 to Spt. 3/’07) to the estimated from normal calculation, thus the agreement between both results is strictly good on the EW type especially. However, on the SN type it is not so good, because of the calculation of S. R. incidence upon roof surface under an assumption of a just horizontal flat surface instead of Quonset hut roof surface to avoid the complexity.
3. Drying a boxed heart squares-larch lumbers

3.1. Calculation of S. R. incidence and estimation of house’s working performance

In case of drying a boxed heart squares-larch lumber, the length of lumber is the same as the board materials, but the cross-section is thick squares (120 mm × 120 mm × 3.65 m) different from the board materials, and moreover, in order to suppress deformation of the lumber when drying under the solar radiation incidence, a thick and large concrete moulded weight stone has to be placed on the stacked lumber. Therefore, a height of the solar lumber drying house needs much taller than that of the 1st proving site in Ashoro. Fig. 9 shows a sketched from of the taller one of EW type set on the 2nd proving site in Asahikawa. Where, Table 3 shows a database of S. R. incidence upon a tilt surface on the drying house in the 2nd proving site. From the Table 3, the intensity of a horizontal total S. R. incidence in Asahikawa during autumn to winter is a little smaller than that in Ashoro, however, the integrated value of through one year is only smaller than that in Ashoro. Therefore, and also considering a contamination of the composite VXUIDFHHODSVHGE\WKUHH\HDUVZHFDQUHFRJQLVHGWKDWWKHHVWLPDWHGRIȘ VC, 0.55 (not 0.6) was put into (τ,α)CSs.

3.2. Performance factors of the 2nd proving site (Asahikawa)

Table 3 shows the intensity of tilt surfaces S. R. incidence in Asahikawa was arranged from a new observation data on the latest 30 years [11]. From the sketch of Fig. 9 and the data of Table 3, we can calculate the performance factors on the drying house as shown in Fig. 10.

From the Fig. 10, it can be seen the same trend as that on the 1st proving site (Ashoro). That is, the VXSHFLDOSHUIRUPDQFHIDFWRUYROXP HWULFVRODUKHDWFROOHFWHGȘ VC (estimated value) is larger in winter and smaller in summer, and yearly averaged value is a little smaller than that of Ashoro.

Table 3. New database (1981-2010) of tilt surface’s S. R. incidence; I(d)MJ/m²d (the 2nd site, Asahikawa; 43°46’N, 142°22’E)

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<tbody>
<tr>
<td>I(H)HT</td>
<td>0° = 0°, α = 0°</td>
<td>5.1</td>
<td>8.8</td>
<td>13.0</td>
<td>15.6</td>
<td>17.5</td>
<td>19.1</td>
<td>17.9</td>
<td>15.4</td>
<td>12.6</td>
<td>8.8</td>
<td>4.8</td>
<td>4.0</td>
<td>11.9</td>
<td></td>
</tr>
<tr>
<td>I(H)WE/WW</td>
<td>α = 90°</td>
<td>6.3</td>
<td>9.9</td>
<td>14.8</td>
<td>16.6</td>
<td>15.8</td>
<td>19.1</td>
<td>18.0</td>
<td>15.9</td>
<td>13.9</td>
<td>10.4</td>
<td>5.7</td>
<td>4.9</td>
<td>12.9</td>
<td></td>
</tr>
<tr>
<td>I(H)WS</td>
<td>α = 90°, a = 0°</td>
<td>4.5</td>
<td>7.8</td>
<td>10.9</td>
<td>9.7</td>
<td>10.2</td>
<td>10.1</td>
<td>9.0</td>
<td>7.7</td>
<td>5.7</td>
<td>3.4</td>
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3.3. High-temperature setting treatment for drying a boxed heart squares-larch lumber

A boxed heart squares-larch lumber after pre-treated by a high temperature under use of a steam dry-kiln by the control of temperature and humidity in a drying room, was dried by loading into a solar lumber drying house. The high-temperature setting treatment which is to be done in an initial stage of drying was tried to decrease outer check on the boxed heart square.
Continuing that process, when aims to dry the lumber until the desired moisture content (MC; dry base: (D.B.)), the steam drying-kiln has to be worked under the control of the lower dry-bulb and wet-bulb temperatures as shown in Fig.11. In general, fuel consumption per hour is the largest rate on an initial process when raw steam is blasted into the drying room directly, and next the rate on a high temperature process is larger. However, those oil consumptions per hour are not so much rate in comparison with the continuing dry process due to the short time of the operation. The time for continuing dry process is required about 144 hours if drying limit is until MC 15% (D. B.) under the condition of Fig. 11, which may be affected by the MC of raw material, the high temperature setting method and the final MC. In this case, the rate between oil consumption at the initial period of the steaming in addition to high temperature setting and that of at the continuing dry process is about 3:7. Therefore, a dry process after the high-temperature setting, if we will use any renewable energy e.g., solar energy on the continuing dry-process, the large benefits can be achieved to reduce a cost for an environmental preservation and energy saving due to decrement of CO₂ exhaustion and oil consumption.

3.4. The results and discussion

(1) From spring to summer (Apr. 7- Jul. 25, 2011)

The drying tests are executed at the Hokkaido Research Organization Forestry Research (HROFR) in Asahikawa (the 2nd proving site). From the boxed heart squares (122 mm×122 mm×3300 mm) pre-treated with high-temperature setting, 154 pieces were selected for measurement of MC, and loaded into the solar lumber drying house as a package piling by 14 rows×11 layers (Fig. 12) [13,14].

In order to observe a degree of the dryness, a specimen of 1m length for the dryness measurement was set in 9th row from the left side and 10th layer from down side. All the test specimens were measured the weight before and after the solar heat drying, when the drying process finished the test piece for MC measurement was cut off and the weight was measured by an oven drying method. Where, after performed by a high-temperature setting, 15 test pieces which are analogous to 25.1-26.1 % were selected and placed in 1, 4, 7, 10 and 11 layers from the down side, and in 1, 8 and 14 rows from the left side, and an outer check was measured before and after the drying process. And more, on three kinds of test pieces provided from some Company, the MC on each point from surface to centre (Moisture distribution) of which was measured. Especially, in this and next chapters the experiments were carried out using only solar heat, without any auxiliary heat.
Fig. 13 shows the outside temperature and inside humidity of the drying house during the test. Averaged temperature and averaged relative humidity inside the drying house were 28.3 °C and 9.0 %, respectively. The highest values of temperature and the lowest relative humidity were 55.9 °C and 3.4 %, respectively. From these values, the equivalent moisture content was obtained as 0.7 %. In general, the dry-bulb temperature and the wet-bulb temperature after a high-temperature setting are 90 °C and 60 °C, respectively, and when applied a temperature-humidity relation, the equivalent moisture content is 3.0 %.

Thus, this experiment indicated the equivalent moisture content of 0.7 % for this solar drying method is instantaneously lower than 3.0 % for usual drying method. Table 4 shows MC of the specimen before and after the solar drying. The averaged MC is 23.4 % before the drying, and that of 10.3 % after drying. Thus, a decrement of MC was 13 % during 109 days. It could hardly recognize the difference in final MC due to a position of package piling. Output for circulation fan for moist air inside the drying house is far less than that of a steam dry-kiln (viz. air velocity through the lumber stack is 0.1-0.2 m/s). This means that an uneven drying tends to occur easily in the drying house. However, low air velocity would not affect the properties of dried specimen, because the specimen pre-treated by the high-temperature setting is already passed over the high MC stage where uneven drying occurred most severely. Moisture distribution within a specimen dried with the solar drying house tends to be more uniform than that with a steam dry-kiln. It is considered that moisture diffusion in the specimen occurs during long drying time in case of an opaque solar lumber drying house. Thus, this is one of the large merits of an opaque solar lumber drying house when drying the lumber pre-treated by high-temperature setting, because uniform moisture distribution is expected to be in high stability of a deformation after planing on the dried lumber.

(2) From winter to spring (Jan. 13-Apr. 10, 2012)

The different points from that during spring to summer are as follows: 1) the specimen length was arranged in 3,000 mm, 2) the middle and lower films of the triple transparent film were damaged due to elapsed three years, so that these parts were renewed, 3) surface of the weight stone placed on package of piling was collared in black, and so on. Fig. 14 shows outside temperature and inside temperature-humidity of the drying house during the test period. Averaged temperature inside the drying house and averaged relative humidity were 10.8 °C and 12.7 %, respectively. When the highest temperature was 42.9 °C, the lowest relative humidity was 3.9 %, and the equivalent moisture content was obtained 0.9 %, which was lower than 3.0 % for a usual drying method instantaneously. A variation of the area of outer check on the surface of specimen couldn’t be found between before and after the drying. Therefore, the high-temperature setting was considered as a suitable technique as a pre-treatment. Table 4 also shows the MC variation of the specimen after and before the drying test from winter to spring. The averaged MC before the drying was 24.9 %, and that after the drying was 15.1 %. Thus, a decrement of MC was 13 %. Values in parentheses are range from minimum to maximum.
was about 10% during 88 days. An effect of the position of package piling could hardly be found similarly to the result from spring to summer. The MC distribution during from winter to spring was similar to the case of spring to summer too.

4. Conclusions
Concerning S. R. incident upon the opaque drying house covered by a composite surface, the principle of volumetric solar heat collected was explained theoretically, and the estimated working performance was calculated referring a database of the tilt surface S. R. incidence, under the application of a new concept of “volumetric solar heat collected”. Consequently, the efficiency of the volumetric solar heat collected $\eta_{VC}$ expressing a working performance attained to a yearly averaged value 140%, i.e., the volumetric solar heat collected is 1.4 times of a S. R. incidence upon the floor area. While, in the real drying house (EW type) constructed on the 1st proving site, a package of board-larch lumber of 8.0 m$^3$ with MC 40% could be dried into 10% or less for two weeks, even in the midwinter, using auxiliary heat. However, in midsummer, the opaque solar lumber drying house can be practically operated without any auxiliary heat. Concerning solar drying on a boxed heart squares-larch lumber (120 mm square × 3.65 m), a package of piling (bulk volume; 10.9 m$^3$) with averaged MC 23.4% which was pre-treated by a high temperature setting could be dried to 10.3% during 109 days from spring to summer, while that of averaged MC 24.9% could be dried to MC 15.1% during 88 days from winter to spring, under solar radiation heat only, nothing any auxiliary heat. We could find out only a little of surface checks and the other defects on the surface of dried specimens, from these facts it was considered that the dried larch lumber of high quality could be produced with the solar drying house. However, a higher working performance containing the cost merit might be needed for the practical use of the opaque solar lumber drying house, for the activations of lumber processing industry in the forest field, and a global utilization of renewable energy i.e., solar energy, biomass energy and so on, in Japan.

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References
[12] NEDO;JWA; (CD-ROM,NP.9703), (Ashoro).