NUMERICAL APPROACH FOR SNOW-MELTING SYSTEM SET UNDER THE PERMIABLE ASPHALT PAVEMENT

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ABSTRACT

In Japan, the Snow-Melting Equipment which the heated circulation liquid is supplied to pipes set under the pavement body has been installed to the lifeline network road. And, the porous asphalt pavement is widely constructed also in the cold and snowy area. As for this kinds of pavement has many gaps in it's body, heat conduction from the ground is prevented and it has a tendency to occur snow coverage.

Until now, we has been developed numerical simulation code which was considered heat transfer between melted snow (=Infiltrated water through the pavement) and pavement body (=Constituent material). And, it was checked that the thermal conductivity of surface layer contributed greatly rather than the size of a cavity with temperature progress.

In this paper, this code was improved and tried several case studies. As for the heat capacity of pavement material (restricted at surface layer) and infiltrated water in cavity, (Even if it was saturated) the heat capacity of saturated water is about 28%. But, from the examination result, the heat loss with drainage is about 15%.

1. INTRODUCTION

In Japan, approximately 28 million people are living in cold and snowy area that occupies about 60% of the country. In order to secure the safe passing space in winter season, the Snow-Melting Equipment has been installed at lifeline network road. The Snow-Melting Equipment which heated circulation liquid is supplied to pipes set under the pavement body is most popular system. And then, this system is able to melt snow and keep anti-freeze at road surface. As a heat source of this system, Groundwater which are mentioned taking advantage of the merit of constant temperature and heated circulation liquid etc. are used. In recent years, from the nuclear power plant accident of the previous Great East Japan Earthquake, ground source heat which is the one of the renewable energy is adopted. For the ground source heat is the low density energy, it need to construct a lot of heat exchangers in the ground. The usage of ground source heat combined with Heat pump system has possibility of reduction for the electric power supply [1].

On the other hand, the porous asphalt pavement is adapted to the lifeline network road. In the summer seasons, because of the rainfall is drained rapidly and water does not remain at road surface, it dose not cause hydroplaning phenomena and avoid reflection of running vehicle's light at night. However, in winter season, since the pavement has many gaps in its body, heat conduction from ground is prevented and melted snow infiltrate into the pavement. If the Snow-Melting Equipment applied to the porous asphalt pavement, it will be able to get safe and comfortable traffic space through all seasons.

It is more significant to consider not only heat source but also the part of pavement which become the heat exchanger. Until now, an applications of numerical analysis for the

Snow-Melting System which applied to the normal (=non infiltration) type pavement can be seen [2],[3],[4],[5]. In case of porous asphalt pavement (=Drainage type which the rain is infiltrate into surface layer), the behaviour of melted snow infiltration have to consider during snow-melting term. This kind of numerical approach has not seen. The simulation code which could consider heat transfer between melted snow (=Infiltrated water through the pavement) and pavement body (=Constituent material) was constructed and it was good agreement with experimental result [6].

In this paper, for the sake of effective planning of Snow Melting System for the porous asphalt pavement, numerical examinations have tried in many cases and it was described to the effective planning of Snow Melting System to the porous asphalt pavement.

<Nomenclature>
T : Temperature [deg.C]
$c\rho$: Volumetric heat capacity[J/(m^3・K)]
α : Heat transfer coefficient between the fluids and particles [W/(m^2・K)]
α_c : Heat transfer coefficient at the road surface[W/(m^2・K)]
λ : Thermal conductivity[W/(m・K)]
D : Thermal dispersivity[W/(m・K)]
a : Average particle diameter[m]
Δhs : Sensible heat [=334 kJ/kg]
u,w : Velocity of saturated water[m/s]
γ : Particle contacted ratio[-]
h_s : Melted snow height[m]
n_s : Heat transfer area between the fluids and particles[m^2/m^3]
n : Number of the particle per unit volume[$1/m^3$]
s : Saturation[-]
ε : Porosity[-]
ρ : Density[kg/m^3]
q_{inf} : Infiltration volume at divided cell[m^3/s]
Q_{inf} : Amount of infiltration[m^3]
IE : Internal Energy[kJ]
η : Ratio of heat loss with drainage[-]

<Subscript>
p : Particle-phase
f : Fluid-phase
s : Snow
w : Water

2. THEORETICAL TREATMENT

2-1. Governing Equations of Temperature Change

The temperature at the surface layer that melted snow infiltrates were distinguished in this numerical model as the particle-phase(=pavement body) and the fluid-phase(=melted snow). Each temperatures were calculated by (Eq-1) and (Eq-2)[6].

<Particle-phase>

$$(1-\varepsilon)\cdot(c\rho)_p\frac{\partial T_p}{\partial t}=(1-\varepsilon)\cdot\lambda_p\cdot\left(\frac{\partial^2 T_p}{\partial x^2}+\frac{\partial^2 T_p}{\partial z^2}\right)-n_s\cdot\alpha\cdot\left(T_p-T_f\right) \qquad \text{(Eq.-1)}$$

<Fluid-phase>

$$\varepsilon\cdot S\cdot(c\rho)_f\frac{\partial T_f}{\partial t}=\varepsilon\cdot D_f\cdot\left(\frac{\partial^2 T_f}{\partial x^2}+\frac{\partial^2 T_f}{\partial z^2}\right)-(c\rho)_f\cdot\left(u\frac{\partial T_f}{\partial x}+w\frac{\partial T_f}{\partial z}\right)-n_s\cdot\alpha\cdot\left(T_f-T_p\right) \qquad \text{(Eq.2)}$$

where n_s ,α , and S are heat transfer area between the fluids and particles, heat transfer coefficient between fluids and particles, saturation at surface layer. Thermal dispersivity D_f is the parameter which has same dimension of thermal conductivity and it means that the heat spreads with flow in porous medium.

Heat transfer area between the fluids and particles n_s is given the following simple relations that the porosity ε and average particle diameter a contacted with γ . An average particle diameter a become smaller, heat transfer area between the fluids and particles become very large. Therefore, for the purpose of correcting, the particle contacted ratio γ is considered.

$$n\cdot\frac{4}{3}\pi\left(\frac{a}{2}\right)^3=1-\varepsilon \qquad \therefore n_s=n\cdot 4\pi\left(\frac{a}{2}\right)^2\cdot\gamma=\frac{6(1-\varepsilon)\cdot\gamma}{a} \qquad \text{(Eq.3)}$$

2-2. Snow Change at the Road Surface (Melting process and Infiltration)

The energy from buried heating pipes was used to melt snow, and the melted snow height h_s is shown the following (Figure1).

$$\alpha_c\cdot\left(T_p-T_s\right)\cdot\Delta x\cdot 1\cdot\Delta t=h_s\cdot\Delta x\cdot 1\cdot\rho_s\cdot\Delta hs \qquad \therefore h_s=\frac{\alpha_c\cdot\left(T_p-T_s\right)\cdot\Delta t}{\rho_s\cdot\Delta hs} \quad \text{(Eq.4)}$$

The melted snow (=water) infiltrates to the surface layer inside at once. At this time, amount $q_{\inf}$ of the inflow is revealed next equation.

$$\Delta x\cdot 1\cdot h_s\cdot\rho_s=\rho_w\cdot q_{\inf}\cdot\Delta t \qquad \therefore q_{\inf}=\frac{\rho_s\cdot h_s\cdot\Delta x\cdot 1}{\rho_w\cdot\Delta t} \qquad \text{(Eq.5)}$$

The velocity of infiltrated water movement u , w estimated in permeable layer. In this paper, in order to deal with simple flow condition, vertical direction of water movement was only considered. Horizontal direction of water flow was ignored ($u=0$). The vertical velocity w changes by response to the amount of $q_{\inf}$. At the bottom of surface layer, melted snow (=water) was drained in an instant according to the infiltration amount.

$$w\equiv\frac{q_{\inf}}{\Delta x\cdot 1} \qquad \text{(Eq.6)}$$

The saturation change takes place by the supplied amount of infiltration. It is considered that the melted snow infiltrate through the gap continuously according to the volume of melted snow. If the snow-melting will be finished completely, it has assumption that the saturation at surface layer is maintained as it is.

$$S = \frac{Q_{\mathrm{inf}}}{(\Delta x \cdot zl \cdot 1) \cdot \varepsilon} \qquad \text{(Eq.7)}$$

where, zl is the thickness of surface layer.

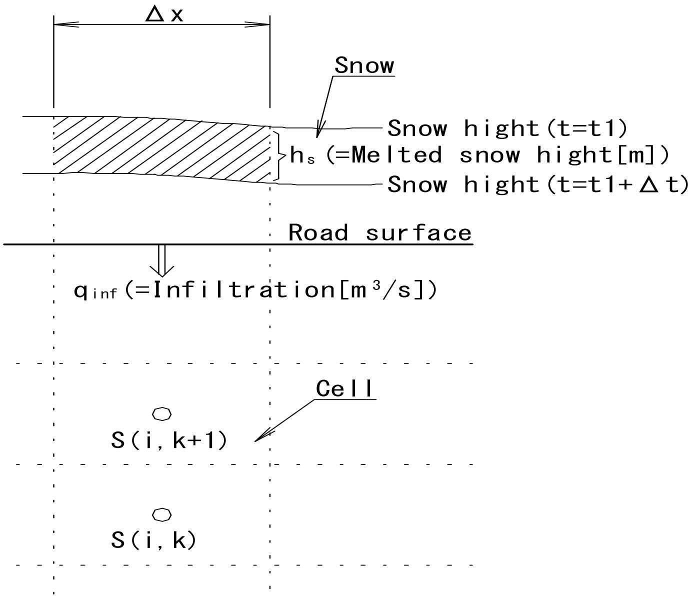

Figure 1 - Snow melting and Infiltration.

The internal energy for the particle-phase(IE_p) and the fluid-phase(IE_f) of surface layer were estimated respectively by (Eq.8). And the ratio of heat loss with drainage was defined as (Eq.9).

$$\begin{aligned} IE_f &= \int (c\rho)_f \cdot \varepsilon \cdot S \cdot \left(T_f - T_p\big|_{t=0}\right) \cdot dV \\ IE_p &= \int (c\rho)_p \cdot (1-\varepsilon) \cdot \left(T_p - T_p\big|_{t=0}\right) \cdot dV \end{aligned} \qquad \text{(Eq.8)}$$

$$\eta = \frac{IE_f}{(IE_f + IE_p)} = \frac{\varepsilon \cdot S \cdot (c\rho)_f \cdot \left(T_f - T_p\big|_{t=0}\right)}{\varepsilon \cdot (c\rho)_f \cdot \left(T_f - T_p\big|_{t=0}\right) + (1-\varepsilon) \cdot (c\rho)_p \cdot \left(T_p - T_p\big|_{t=0}\right)} \qquad \text{(Eq.9)}$$

where, for example, $T_p\big|_{t=0}$ means the initial temperature of particle-phase.

3. NUMERICAL ANALISIS

3.1. Numerical Model and Analysis Conditions

The numerical model which has some courses is two-dimension (Figure2). This model could consider the material properties (ex. thermal conductivity, volumetric heat capacity and porosity etc.) at each courses. The infiltration of melted snow occurs at the surface layer only, and at the other layers no infiltration occurs. Melted snow (=water) is drained at the surface layer's bottom in proportion to infiltration. The snow height upon the road surface changes by heat flux from the road surface. At heating pipe cell, constant temperature was set as heat source. The conditions(Inlet Temperature, amount of supply volume) were able to give arbitrarily possible.

The initial condition of the pavement temperature gave uniform. The boundary conditions at pavement side and the bottom were given heat transfer condition that estimated from the experimental results. And at the road surface, heat transfer coefficient was given. The heat transfer coefficient was determined by trial and error that referred Experimental results[7]. The other parameters were given as Table 2.

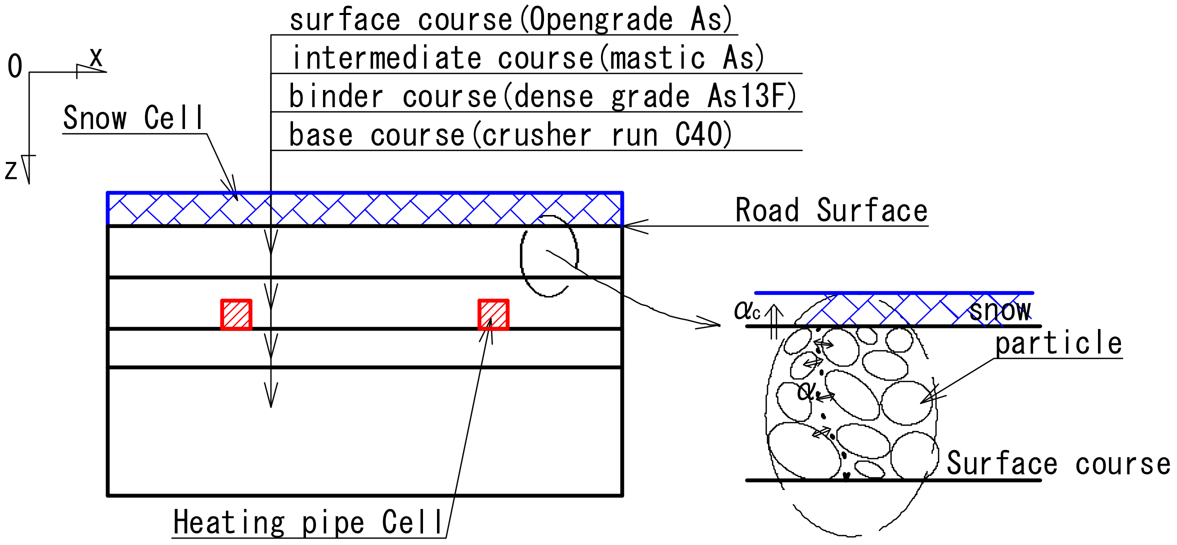

Figure 2 - Numerical Model Section.

Table 1 - Property of the Pavement materials.

	Open grade As	Mastic As	Dense grade As
Appearance Thermal Conductivity [W/(m·K)]	2.02	1.52	2.79
Density[kg/m^3]	2,177	2,367	2,347
Specific Heat[kJ/(kg·K)]	1.72	0.9	2.38
Porosity[-]	0.214	-	0.043

Table 2 - Parameter of Calculation conditions.

		Parameter	Remark
α_c	[W/(m^2·K)]	35(Melting term) 5(After melted)	Refereed by Experimental Obs.[7]
α	[W/(m^2·K)]	10	Yokoyama et.al[8]
a	[m]	1.3×10^{-3}	
γ	[-]	0.01	
ρ_w	[kg/m^3]	1,000	
ρ_s	[kg/m^3]	400	Experimental Obs.
D_f	[W/(m^2·K$^{)}$]	10	Yokoyama et.al[8]

3.2. Compare the Experimental Observations to Numerical Output

3.2.1. Particle-phase Temperature and Remain Snow Weight Change at road Surface.

Figure 2 showed the particle-phase temperature, remained snow weight change at road surface, and the counter map(After heating t=2[h], 4[h], 8[h]). Plot shows experimental observations(Supply to pipes as heat source :30[deg.C], 20[L/min]), and the Line is numerical output. It is able to conform that numerical output temperature of each points had good agreement. The temperature at road surface where above the heating pipe(Ab_1$_p$) raised rapidly after 4 hours heating. This means, snow melting is end at that point. But the middle of heating pipes(Bet$_p$) is under snow melting. The remained snow weight at surface decreased, and about 6.7 hours after, snow melting was completely finished.

Temperature progress of pavement section was confirmed by the counter maps. Dash-dot lines showed layer bounder that showed Figure 1. In a surface layer, for example, while snow melting(t=2[h]), the influence of melted water infiltration was not seen so clear.

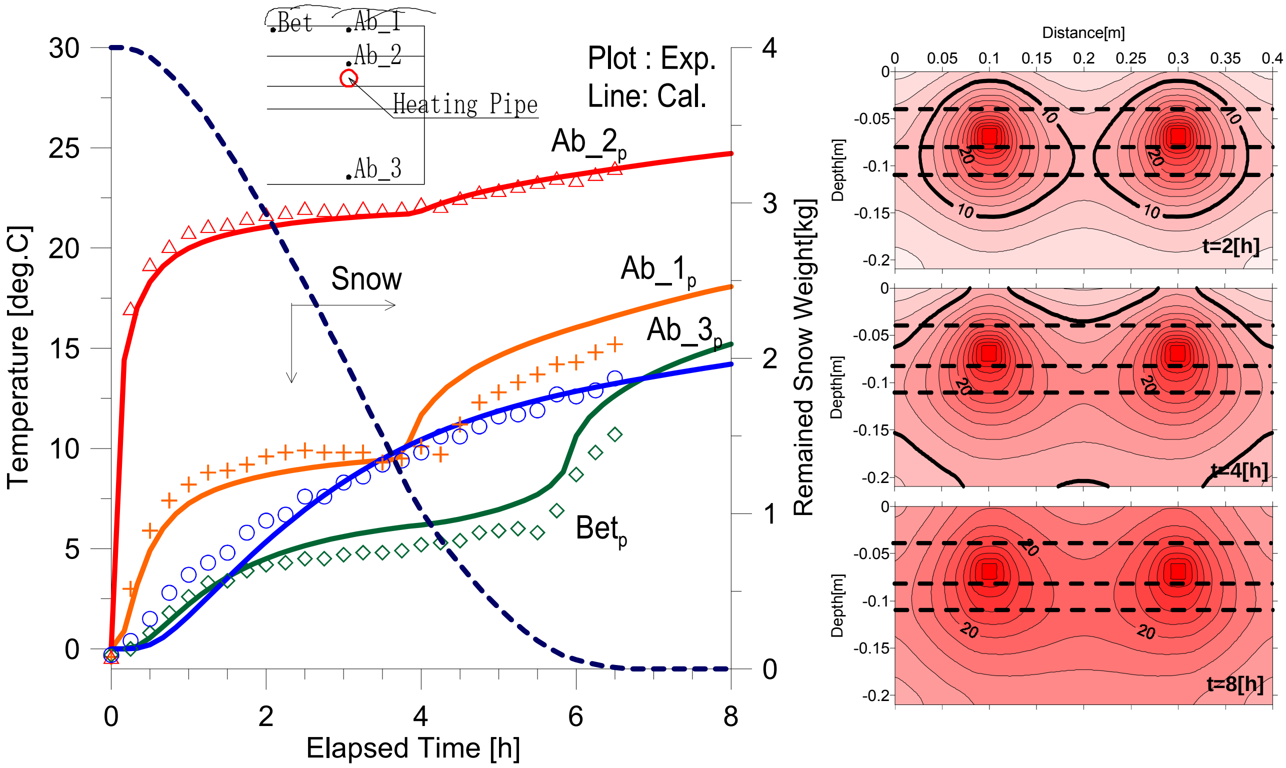

Figure 2- Compartments of Temperature change and Temperature Counter.

3.2.2. Saturation and Drainage Temperature Change at Surface Layer

Figure 3 shows saturation change at surface layer. The saturation changed by according to the heat flux and as the Eq.7 showed, it was equalized for vertical direction at surface layer. As a result, amount of snow melting infiltration occurred and it had deference at each point. The saturation progress at above the heating pipe was faster than middle of heating pipes. In the early stages of heating, the big change of saturation could be checked. About 4 hours later, above pipes was already saturated, but the middle of heating pipe, because of the heat flux was smaller than above pipe, the saturation was about 0.7. 5 hours heating, all the surface layer was saturated. In this numerical model, if the infiltration from road surface had lost, the saturation at pavement was maintained as S=1, until the calculation is finished.

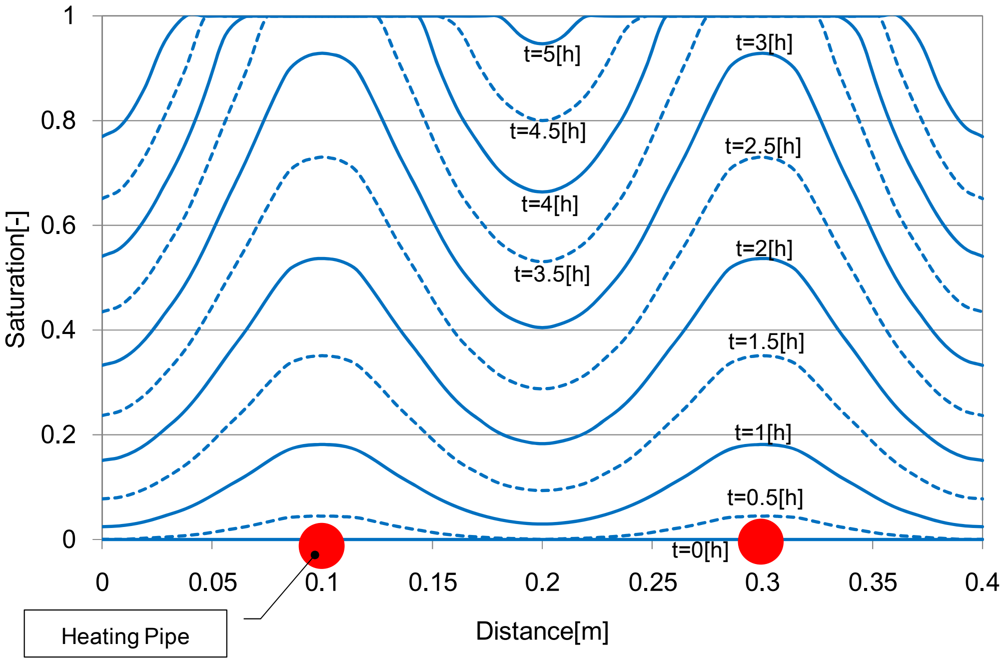

Figure 3- Distribution of Saturation.

The drainage temperatures and average saturation in surface layer change was showed in Figure 4. In this case, the drainage temperature which at above heating pipe(Tf_pipe) and middle of heating pipes(Tf_mid) were about 4[deg.C] after 4hours heating. It mentions above, the infiltrated water reached at the surface layer's bottom, and it was drained immediately. While permeating, melted water get an energy by heat transfer among particle-phase and fluid-phase, so the fluid-phase temperature raised. Like the particle-phase temperature of a road surface, the temperature difference between at above heating pipe and at the middle pipes was not seen greatly.

As the whole surface layer's saturation, it was averaged. Average saturation changed almost linear. After 4 hour heating, most surface layer was saturated.

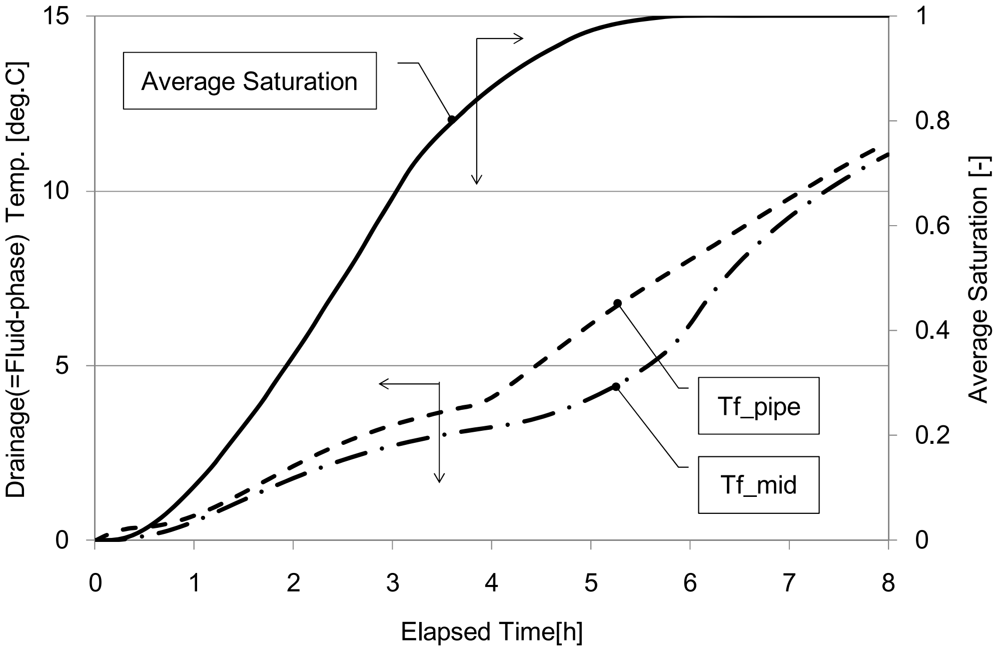

Figure 4- Drainage Temperature and Average Saturation Change.

3.2.3. *Internal Energy and Heat Loss with Drainage*

Since a particle-phase temperature and fluid-phase temperature were able to deal with separate, the internal energy based on each temperature was computable. Figure 5 showed internal energy of particle-phase(IE_p) and fluid-phase(=heat loss with drainage), IE_f) changes, and the ratio of heat loss with drainage change. The situation which each internal energy change(IE_p, IE_f) increased with time was able to checked. The internal energy of particle-phase(IE_p) increased rapidly after 4 hours. The internal energy of fluid(=Heat loss with drainage) was smaller than particle-phase's internal energy(IE_p). The internal energy of whole pavement body was dominated by particle-phase's internal energy(IE_p).

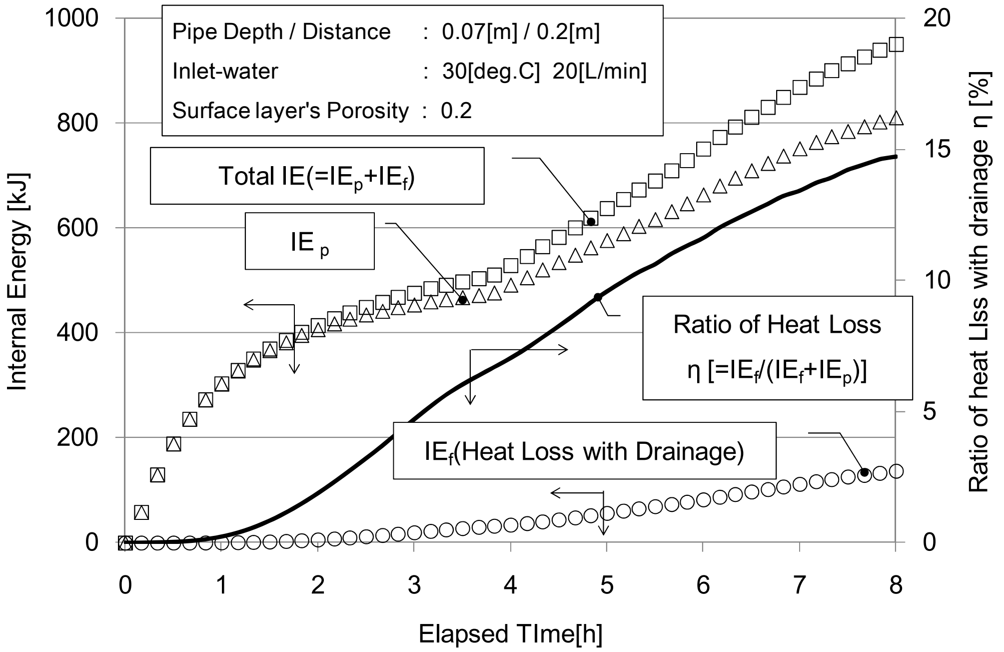

Figure 5- The Internal Energy and Heat Loss with Drainage.

In this model case, if the porosity in pavement was saturated, and the temperature of a particle-phase and a fluid-phase equally, the ratio of heat loss with drainage become 28%(Maximum). 6.7 hours after heating that melting snow on road surface was completed, the ratio of heat loss with drainage was 13.2%.

3.3. Case Studies

3.3.1. The Effect of Porosity and Pipe Interval

In order to confirm the effect of porosity and pipe interval, several case studies were executed. The relation of average degree of saturation and the ratio of heat loss with drainage was shown in Figure 6. The surface layer's porosity(0.1[-], 0.2[-], 0.3[-]), and the pipe interval(0.1[m], 0.2[m], 0.3[m]) were changed.

As for the difference of porosity(expressed symbols), the porosity become bigger, the ratio of heat loss with drainage had increasing tendency(Pipe interval : 0.2[m] and ε=0.1, 0.2, 0.3). When a cavity was large, time was required by saturation and during this process, ratio of heat loss become larger than the case of small porosity. When a cavity was small, ratio of heat loss increased slightly, and then it increased greatly after saturation. The way of operation that a degree of saturation does not become large leads to stopping a heat loss.

The difference pipe interval(ε=0.2 :pipe interval=0.1[m], 0.15[m], 0.2[m]) were expressed Line. In case of pipe interval was near, rapid saturation raise could seen, and increase of the heat loss was confirmed. The pipe interval become near, because of the infiltration of melted snow(=water) takes place rapidly as a result of heating to road surface uniformly. Then, it was infiltrated through the high temperature area, the heat exchanged water was drained. So, it was thought that the ratio of heat loss become rapidly increased.

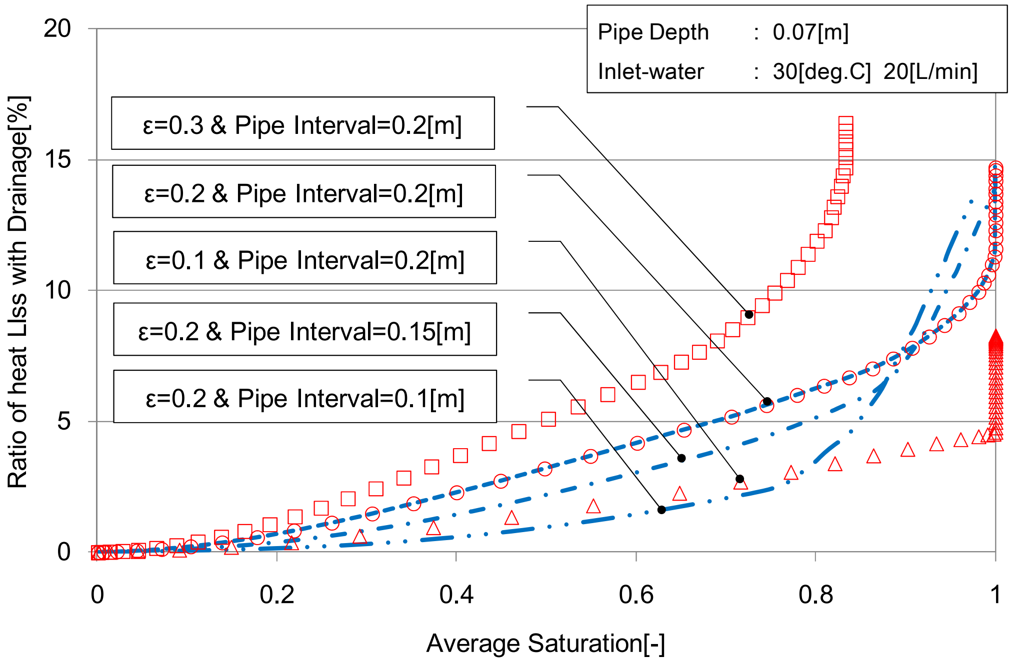

Figure 6- Effect of Porosity and Pipe Interval.

Figure 7 showed temperature counter maps(After 2[h] heating) that differs heating pipe interval. The equivalent temperature line 10[deg.C] was expressed thick line. The dotted line means boundary of layer.

The pipe interval become near, the road surface temperature at the middle pipes was higher, and this means that the road surface was heated equally.

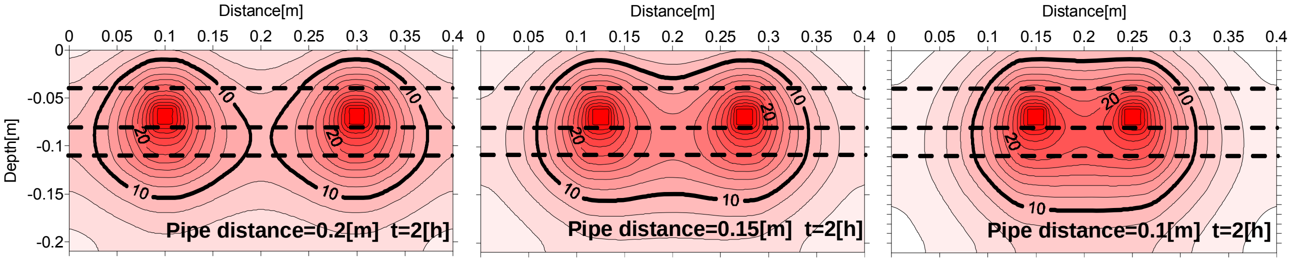

Figure 7- Temperature Distribution by Heating Pipe Interval.

3.3.2. *The Effect of Supplied Temperature to Pipe*

About the case that the supply temperature to the pipe differs, the ratio of heat loss with drainage were shown in Figure 8. Snow melted time which confirmed by the remained snow weight in each case were showed together. The ratio of heat loss with drainage was estimated at this time.

According to the supply temperature, the ratio of heat loss with drainage were 13.2~14.1%. Although the ratio of heat loss with drainage did not change a lot with supply water temperature, when the supply temperature become lower, the ratio increased about 7%.

In case of planning snow melting equipment to this kinds of porous asphalt pavement, it is necessary to estimate larger about 15% for a heat requirement.

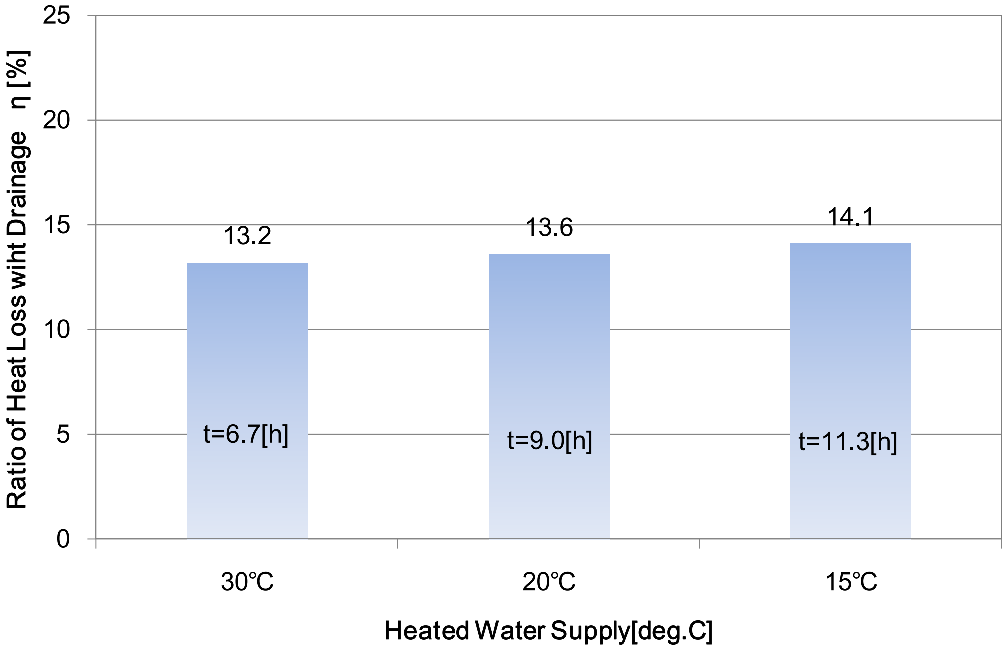

Figure 8- The Ratio of Heat Loss with Drainage according to Supply Temperature.

4 CONCLUSIONS

(1) The numerical model was improved, and then it was able to judge the snow melting progress and take into consider the saturation change that occurred according to heat flux in permeable layer.

(2) By the internal energy of particle-phase and fluid-phase, the ratio of heat loss with drainage was evaluated quantitatively by the two-phase model. According to the water supply temperature, about 13~14% of heat loss with drainage was confirmed. The pipe's inlet temperature become lower, the heat loss with drainage increase several percent.

(3) Effective planning for the Snow-Melting System to the porous asphalt pavement, it is necessary to estimate larger about 1/6 percent for a heat requirement, a little more than conventional treatment.

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