HYDRAULIC CHARACTERISTICS OF SNOW LYSIMETERS

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ABSTRACT

A snow lysimeter is a pan or container placed below the snow surface to intercept and collect water moving downward through the snow, for measurement purposes. The characteristics of lysimeter operation are derived from porous media theory with some recent measurements of ripe snow properties. Lysimeter-induced hydraulic effects are discussed for both zero-tension and tension lysimeters. Start-up time following lysimeter installation in snow is shown to be sensitive to both flux and water pressure at the lysimeter base. The flow-collection coefficient becomes essentially unity when the raised rim of an unenclosed lysimeter is constructed to equal the pressure-gradient zone in height. The pressure-gradient zone thickness varies from 0.02 to 0.18 m, depending on flux and lysimeter base pressure. It is sensitive to hysteresis in the relation of permeability to water pressure for snow.

INTRODUCTION

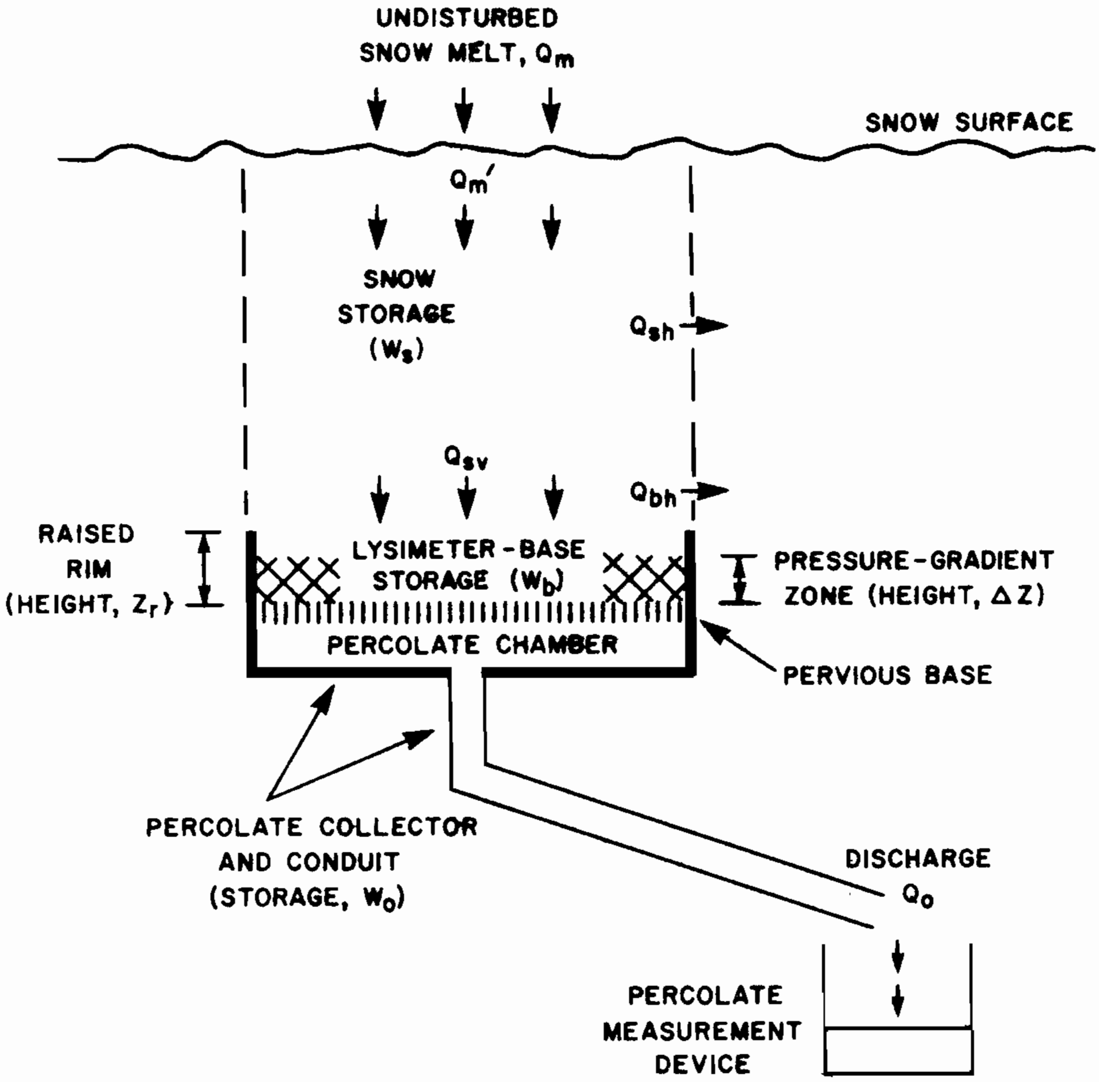
A lysimeter is a 'vessel or container placed below the ground surface to intercept and collect water moving downward through the soil' (World Meteorological Organization, 1974). Similarly, a snow lysimeter can be defined as a pan or container placed below the snow surface to intercept and collect water moving downward through the snow, for measurement purposes. Kohnke et al. (1940) listed three kinds of construction for soil lysimeters. (1) Filled-in, where the container is filled with disturbed soil. In snow physics, it has been used for precise measurements of processed uniform snow (Colbeck and Davidson, 1972). (2) Monolith, where the container is built around an in-situ block of soil. The monolith snow-lysimeter contains a block of snow which has been either carefully removed from a snowpack (Quick, 1970) or accumulated inside the device between sidewalls which can be moved up or down with the snow surface (Haupt, 1968). (3) Unenclosed, where 'the soil is left in-situ and a percolate collecting funnel is placed under it, but no sidewalls separate a definite soil block from the adjoining soil'. The unenclosed lysimeter is installed either on the ground before snow falls begin (Rockwood et al., 1954) or within the snowpack at the level required (Wankiewicz, 1976). The lysimeter base is surrounded by a raised rim to block lateral flow in the pressure-gradient zone of the overlying snow. The feasibility of eliminating the lysimeter-induced flow disturbance with a relatively low rim, reflects the coarse grained nature of snow. Most soils are much finer grained and would require too high a rim for the lysimeter to be considered as unenclosed.

A snow lysimeter consists of: a pervious base of area A_L and associated percolate collector; either a raised rim or sidewalls; a percolate measurement device; and occasionally provision for measuring the weight of the overlying snow. Figure 1 illustrates the case of the unenclosed lysimeter.

A melt-collection coefficient, C_m, can be defined in terms of the undisturbed net snow melt above the lysimeter, Q_m (m^3s^{-1}), and the lysimeter discharge Q_o:

FIGURE 1

SNOW LYSIMETER COMPONENTS



$$C_m = Q_o/Q_m \tag{1}$$

C_m is composed of the three factors: (1) disturbance-melt factor, f_d, given by Q_m'/Q_m to account for lysimeter melt disturbance; (2) transfer factor, f_t, given by Q_{sv}/Q_m', to account for losses to snow storage and lateral flow along icy layers; (3) flow-collection coefficient, C_v, defined by

$$C_v = Q_o/Q_{sv} \tag{2}$$

to account for losses to lysimeter storage and to lysimeter-induced lateral flow. Q_{sv} is the flow at the lysimeter depth in the absence of the base unit. Hence

$$C_m = f_d \, f_t \, C_v \tag{3}$$

Since the melt rate is sensitive to snow surface disturbance, the unenclosed lysimeter has been the most frequently used in snow, in spite of the possibility of unrestricted lateral flow along icy layers. For steady flow, the unenclosed lysimeter has $f_d = 1$ and f_t dependent on snow properties, while the monolith lysimeter has $f_d > 1$ and $f_t = 1$.

When the snow is supported by a perforated base above a chamber containing water at zero pressure the device can be called a zero-tension lysimeter. A drip pan is a similar device except that the percolate drips into an air chamber instead (e.g. the Lower Meadow lysimeter in Rockwood et al., 1954). When information is required for flow waves over a small scale or with minimum distortion the water in the chamber may have to be maintained at a negative pressure. The perforated base would then be a porous plate or membrane with pores small enough to stop air entry into the water chamber below. Often used in soil plot studies (e.g. Cole, 1958), the tension lysimeter has been used to measure flux in a snowpack by Wankiewicz (1976) and in the laboratory by Colbeck (1974).

The following hydraulic effects associated with the introduction of a pervious lysimeter base into a snowpack will be derived: installation start-up time, dynamic response time, pressure-gradient zone thickness, and flow-collection coefficient. Thermodynamic effects on the snow structure, in the pressure-gradient zone, are beyond the scope of this paper (see Colbeck, 1973). The drainage will be assumed to occur uniformly over the lysimeter base to simplify analysis to one-dimension. The analysis would have to be amended for application to impervious base lysimeters which slope to a drain to include the percolate's horizontal movement in the snow itself.

The upper surface of the pervious base of the lysimeter will be referred to as the lysimeter interface. The water pressure there is p_i. The characteristics of snow lysimeters will be studied in terms of these limiting interface pressures: $p_i = 0$, the zero-tension lysimeter, and $p_i = -\infty$ for a tension lysimeter. The devices are assumed to be located in a deep homogeneous snow cover with no boundary effects from the ground or upper snow surface. Let the input flux to the lysimeter base be V_{sv}, given by Q_{sv}/A_L. The diurnal melt cycle will be represented by the flux values $V_{sv} = 0.05 \times 10^{-6}$ ms^{-1} for the early morning and $V_{sv} = 1.0 \times 10^{-6}$ ms^{-1} for the early afternoon, the flux assumed to be pseudo-steady at these two times. Wherever possible, corresponding values of the dimensionless parameter $(-V/\alpha k_s)$ will be used where the intrinsic permeability $k_s = 9.1 \times 10^{-10}$ m^2. This k_s is for a layer of 1.0 mm glass beads with a porosity of 0.37 (de Vries, 1975, personal communication). $\alpha = \rho_w g/\mu_w = 5.47 \times 10^6$ m^{-1} s^{-1} for water at 0.0°C.

ANALYSIS OF LYSIMETER STORAGE

The snow water pressure p_w is defined relative to air pressure P_a, i.e. $p_w = P_w - P_a$ where P_w is the absolute water pressure. For steady flow conditions, Darcy's equation for vertical flow is

$$V = -\alpha k_w \left(\frac{1}{\rho_w g} \, dp_w/dz + 1\right) \tag{4}$$

given as a function of both the gradient, dp_w/dz with respect to height z above a datum, and the permeability to the liquid, k_w. Liquid water content by volume, Θ, is best considered in the form of effective saturation, S^*, defined by

$$S^* = (\Theta - \Theta_i)/(\phi - \Theta_i) \tag{5}$$

where Θ_i is the irreducible water content and ϕ is the snow porosity.

The permeability k_w can be written as a function of either S^* or p_w

$$(k_w/k_s) = S^{*\varepsilon} \tag{6}$$

where $\varepsilon = 3$ from drainage wave measurements for homogeneous snow by Colbeck and Davidson (1972). On the other hand, the $k_w(p_w)$ relation exhibits hysteresis and may have to be approximated by

$$(k_w/k_s) = (-a/p_w)^{b} \tag{7}$$

with specific 'a' and 'b' coefficients for each range of p_w over which the power expression applies. Dimensionless parameters can be used if hysteresis is ignored. Then 'b' equals the pore size distribution index, η, and 'a' equals the bubbling suction, τ_b. $\eta \approx 13$ for ripe snow (Wankiewicz, 1976). τ_b is the suction at which the large pores empty or fill with water. For saturated snow, Equation 7 is replaced with

$$(k_w/k_s) = 1 \qquad \text{when } p_w \geq -\tau_b \tag{8}$$

For the pressure range(s) for which Equation 7 applies, a gravity-flow pressure(s), p_v, can be defined in terms of the scaled flux $(-V/\alpha k_s)$.

$$p_v = -a(-V/\alpha k_s)^{-1/b} \tag{9}$$

The corresponding gravity-flow effective saturation is

$$S_v^* = (-V/\alpha k_s)^{1/\varepsilon} \tag{10}$$

Lysimeters increase (decrease) the water stored in the overlying snow because p_i is larger (smaller) than p_v. The lysimeter-base storage w_b $(= W_b/A_L)$, is given by

$$w_b = (\phi - \Theta_i)\int_0^{\infty} (S^* - S_v^*)dz \tag{11}$$

To include hysteresis, the integration is performed separately over each range of constant a and b. Substituting dz from Equation 4 and using Equations 5 to 10 we get the storage, $w_b(p_1, p_2)$ stored in the height interval defined by the pressures p_1 and p_2, as a dimensionless parameter.

$$w_b(p_1, p_2)\rho_w g/a(\phi - \Theta_i) = (-V/\alpha k_w)^{1/\varepsilon - 1/b}\int_{p_1/p_v}^{p_2/p_v} \{x^{-b/\varepsilon} - 1\}/\{1 - x^b\}dx \tag{12}$$

where $x = (p_w/p_v)$.

If $p_1 > -\tau_b$, the lower limit is changed to $(-\tau_b/p_v)$ and the term:

$$(1 + p_1/\tau_b)\{1 - (-V/\alpha k_s)^{1/\varepsilon}\}/\{1 - (-V/\alpha k_s)\} \tag{13}$$

is added to the right side of Equation (12). The percolate collection and conduit storage, W_o depends on detailed design of the device and will not be considered here. The hydraulic effects can be derived from these relations.

LYSIMETER START-UP TIME

Values of lysimeter-base storage (w_b) are given in Table 1 for two lysimeter pressures (p_i) and two fluxes. w_b was calculated from Equations 12 and 13 with $\varepsilon = 3$ and $b = 13$. The table explicitly shows the effects of snow properties except for hysteresis. The tabulated values for $p_i = -\infty$ can be used for finite p_i to less than 5% error as long as $p_i > 1.4\ p_v$.

TABLE 1

LYSIMETER-BASE STORAGE FOR TWO INTERFACE PRESSURES
(ignoring hysteresis effect)

SCALED INPUT FLUX ($-V_{sv}/\alpha k_s$)	$w_b\rho_w g/\tau_b(\phi - \Theta_i)$	
	$p_i = 0$	$p_i = -\infty$
0.01×10^{-5}	1.28	-0.62×10^{-3}
0.1×10^{-5}	1.27	-1.13×10^{-3}
1.0×10^{-5}	1.24	-2.04×10^{-3}
10×10^{-5}	1.17	-3.67×10^{-3}
100×10^{-5}	1.10	-6.57×10^{-3}

The lysimeter will not correctly respond to hydrometeorologic events until after the necessary water storage has been supplied following instrument installation in the snowpack (alternatively, following coverage by a snowfall(s)). According to the table, a zero-tension lysimeter must be initially primed with $\sim 1.2\tau_b(\phi - \Theta_i)/\rho_w g$ metres of water. An index of the response of a lysimeter to being inserted into a snowpack through which is percolating a flux V_{sv}, is given by

$$t_s = |w_b/V_{sv}| \tag{14}$$

This definition is based on dimensional considerations. The lysimeter discharge Q_o, would be representative of the flow $V_{sv}A_L$, only for times large compared to the start-up time t_s, since some outflow occurs as V_{sv} supplies the necessary storage.

Values of t_s are listed in the second column of Table 2.

TABLE 2

LYSIMETER START-UP TIME
($\phi - \Theta_i = 0.37$ and $k_s = 9.1 \times 10^{-10}$ m^2)

INPUT FLUX ($-V_{sv}$)	IGNORING HYSTERESIS EFFECT (τ_b = 300 Nm^{-2})	INCLUDING HYSTERESIS EFFECT (Figure 2)
$p_i = 0$		
0.05×10^{-6} ms^{-1}	2.8×10^5 s	2.9×10^5 s
1.0×10^{-6} ms^{-1}	1.3×10^4 s	1.3×10^4 s
$p_i = -\infty$		
0.05×10^{-6} ms^{-1}	460 s	770 s
1.0×10^{-6} ms^{-1}	49 s	132 s

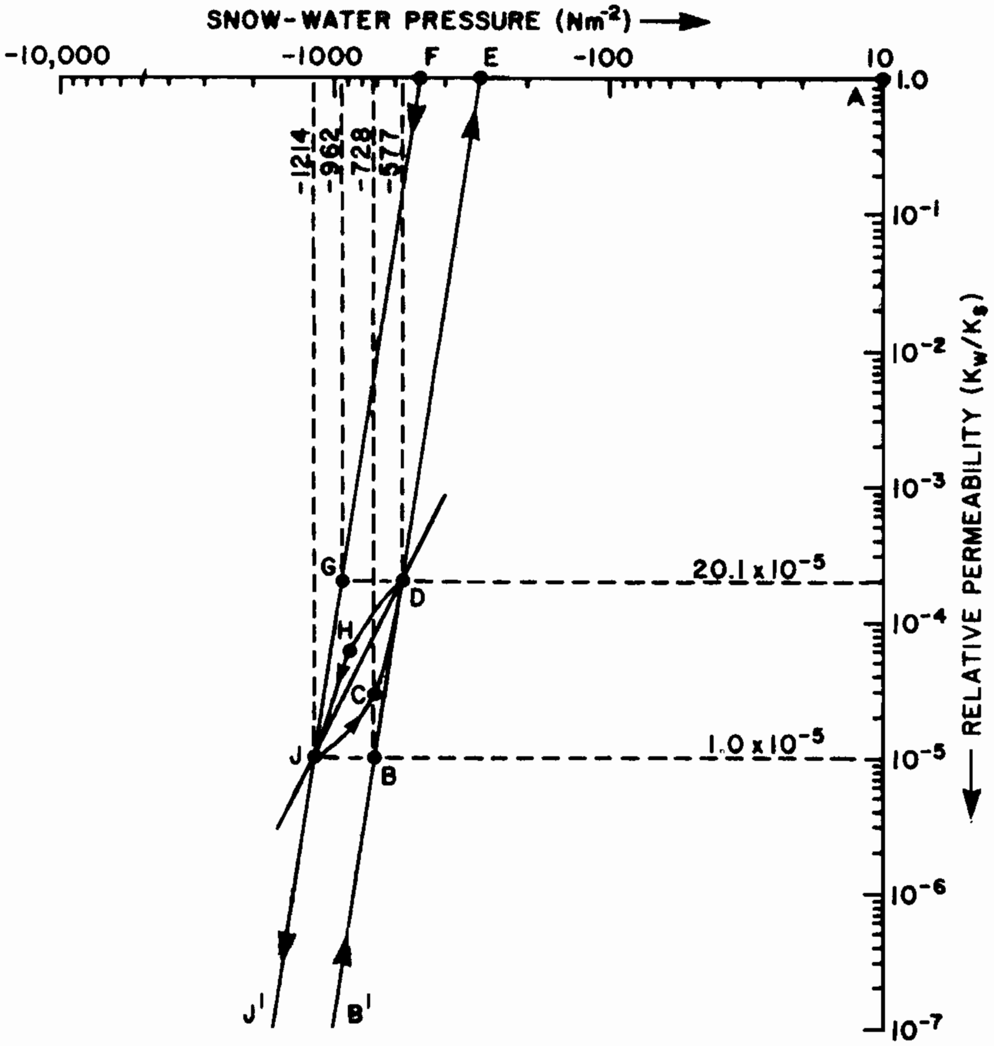
Note that zero-tension lysimeters have start-up times of several days for the drier snow range! Tension lysimeters have w_b and hence t_s that are several orders of magnitude smaller. The installation-hysteresis effect will be evaluated for several cases of interest in the next section.

HYSTERESIS AND WATER STORAGE

The hysteresis in the $k_w(p_w)$ relation calculated by Wankiewicz (1978b), is shown in Figure 2. The calculations were idealizations of results from flux and water pressure measurements in ripe snowpacks by Wankiewicz (1976). Very dry snow (point B' in the figure), which is subsequently wetted, progressively follows the boundary wetting curve B'BDEA to point A where $p_w = 0$. Point E is at the wetting bubbling suction. W_b in Table 1 had been calculated using the boundary wetting curve. On the other hand, snow starting at A and progressively dried, follows the boundary drying curve AEFGJJ'. Point F is at the drying bubbling suction.

FIGURE 2

HYSTERESIS IN THE $k_w(p_w)$ RELATION FOR RIPE SNOW



With alternate wetting and drying, the snow follows loops between the two boundary curves. The loop JCDHJ represents a diurnal melt cycle in undisturbed snow from early morning (J) to early afternoon (D) to early morning the next day (J). For quasi-steady flow (points J and D), (k_w/k_s) equals $(-V/\alpha k_s)$ by Equation 4, since $dp_w/dz = 0$ in the bulk of the snow (Wankiewicz, 1978b).

We will now calculate the hysteresis effect on $w_b/(\phi - \Theta_i)$ associated with lysimeter installation. Installation-hysteresis effects involve a single wetting/drying reversal. As an example of the computation procedure, consider the case of a zero-tension lysimeter in snow characterized by the relation in Figure 2, installed in the early morning ($-V_{sv}/\alpha k_s = 1.0 \times 10^{-5}$ or point J). The overlying snow is wetted by the introduction of the $p_i = 0$ interface, reversing the overnight drying trend. The snow at each level above the device begins at point J and follows part of JCDEA. The lower the level, the closer the final point is to point A. JCDEA is approximated by JDEA consisting of three pressure ranges. The contribution to $w_b/(\phi - \Theta_i)$ from JD is given by Equation 12 with the coefficients, $a = 69.8$ Nm^{-2} and $b = 4.03$; the limits, $p_1 = -577$ Nm^{-2} and $p_2 = -1214$ Nm^{-2}; and $p_y = -1214$ Nm^{-2} from $(-V_{sv}/\alpha k_s) = 1.0 \times 10^{-5}$. $w_b/(\phi - \Theta_i)$ from DE is based on $a = 300$ Nm^{-2} and $b = 13$; $p_1 = -300$ Nm^{-2} and $p_2 = -577$ Nm^{-2}; and $p_y = -728$ Nm^{-2} for the same $(-V_{sv}/\alpha k_s)$. $w_b/(\phi - \Theta_i)$ from EA is given by expression 13 multiplied by $a/\rho_w g$ with $a = 300$ Nm^{-2}; $p_1 = 0$; and the same $(-V_{sv}/\alpha k_s)$. The complete $w_b/(\Theta - \phi_i)$ from $z = 0$ to ∞ is 0.0389 m. On the other hand, ignoring hysteresis (i.e using BDEA instead) yields $w_b/(\Theta - \phi_i) = 0.0378$ m. The base storage and hence start-up time for a zero-tension lysimeter with $(-V_{sv}/\alpha k_s) = 1.0 \times 10^{-5}$, is increased by the factor 1.03 by the installation-hysteresis effect.

Both $w_b/(\Theta - \phi_i)$ and t_s are increased by the following factors for some additional cases calculated in a similar way to the example, including using JD as an approximation to either JCD or DHJ. A zero-tension lysimeter installed when $(-V_{sv}/\alpha k_s)$ is 20.1×10^{-5} (point D in Figure 2), 1.00; a tension lysimeter installed when $(-V_{sv}/\alpha k_s)$ is 1.0×10^{-5} (point J), 1.67; a tension lysimeter installed when $(-V_{sv}/\alpha k_s)$ is 20.1×10^{-5} (point D), 2.69.

Values of t_s, including the installation-hysteresis effect, are listed in the third column of Table 2. It appears that the effect on t_s is small enough to be ignored, considering the fact that t_s is itself only an index of the response. The hysteresis effect of multiple wetting/drying reversals due to melt cycles subsequent to installation have not been considered.

DYNAMIC RESPONSE

The lysimeter response will now be discussed for a sudden increase in the input flux from V_0 to V_1, such as occurs with the arrival of a wetting front at the lysimeter depth D_L. The approach used by Colbeck (1974) for the response of zero-tension lysimeters will be amplified in this section. The dynamic response time t_d, is defined in terms of the change in water storage $(w_{b1} - w_{b0})$, above the interface.

$$t_d = |(w_{b1} - w_{b0})/(V_1 - V_0)| \qquad (15)$$

Table 1 supplies values of w_b for t_d, ignoring the hysteresis effect. The table shows that $(w_{b1} - w_{b0})/(V_1 - V_0)$ is always negative so that t_d is an index of how early the wetting front arrives due to the presence of the lysimeter. For a translatory wave penetrating the snow at speed

$$U = (V_1 - V_0)(\Theta_1 - \Theta_0) \qquad (16)$$

the ratio of response time to travel time is given by

$$t_d\, U/D_L = |w_{b1} - w_{b0}|/(\Theta_1 - \Theta_0)D_L \qquad (17)$$

For a sudden increase in flux from $V_{sv} = 0.05 \times 10^{-6}$ ms^{-1} to 1.0×10^{-6} ms^{-1}, the dynamic response time for a zero-tension lysimeter would be 950 s, assuming snow with

τ_b = 300 Nm^{-2}, $(\phi - \theta_i)$ = 0.37, and k_s = 9.1 x 10^{-10} m^2. The dynamic response time for a tension lysimeter would be 26 s for the same conditions. t_d U/D_L would be 13% for a zero-tension lysimeter installed at D_L = 0.5 m. The zero-tension lysimeter should yield approximate measures of wetting front travel times, provided D_L is not too small. t_d U/D_L becomes 0.36% for a tension lysimeter. The effect of multiple-reversal hysteresis on t_d is difficult to quantify and has not been attempted.

THICKNESS OF THE PRESSURE-GRADIENT ZONE

The pressure profile in snow above an interface at pressure p_i was derived by Wankiewicz (1978b) for steady flow V. He showed that (a) significant water pressure gradients, i.e.

where $$\frac{1}{\rho_w g} |dp_w/dz| > 0.1 \qquad (18)$$

are confined to a relatively thin pressure-gradient zone of thickness Δz; and that (b) p_w is independent of depth at higher levels in the snow. At the top of the pressure-gradient zone, $(p_w/p_v) = (0.9)^{1/\eta}$ and $(1.1)^{1/\eta}$ for wetting and drying interfaces, respectively.

$$\Delta z = 1.16\ (p_v/\rho_w g) \qquad \text{when } p_i = 0 \qquad (19)$$

with η = 13 snow, ignoring any hysteresis effect (Figure 3 in Wankiewicz, 1978b). The corresponding Δz relation,

$$\Delta z = 0.20\ (p_v/\rho_w g) \qquad \text{when } p_i = -\infty \qquad (20)$$

is six times smaller. p_v was related to flux in Equation 9.

These relations were used to calculate the Δz listed in the second column of Table 3.

TABLE 3

THICKNESS OF THE PRESSURE-GRADIENT ZONE
(η = 13)

SCALED FLUX $(-V_{sv}/\alpha k_s)$	IGNORING HYSTERESIS EFFECT (τ_b = 300 Nm^{-2})	INCLUDING HYSTERESIS EFFECT (Figure 2)
p_i = 0		
1.0 x 10^{-5}	0.0862 m	0.1840 m
20.1 x 10^{-5}	0.0683 m	0.0683 m
$p_i = -\infty$		
1.0 x 10^{-5}	0.0149 m	0.0248 m
20.1 x 10^{-5}	0.0118 m	0.0420 m

Δz in the third column was calculated including the installation-hysteresis effect, by a similar approach to that used in the fourth section, using a pressure profile formula (Equation 9 in Wankiewicz, 1978b). It can be seen from Table 3 that Equations 19 and 20 should only be used as a general guide to the dimensionless parameter $(\Delta z \rho_w g/p_v)$. Hysteresis should be included in calculations for specific cases.

When the height of the raised rim enclosing the lysimeter interface equals the thickness of the pressure-gradient zone associated with the lowest flux of interest, the flow-collection coefficient C_v becomes essentially unity. The pressure at greater heights varies by less than 1% from that of the surrounding snowpack according to a discussion of pressure profiles in Wankiewicz (1978b).

Assuming steady flow the lysimeter discharge, Q_o is given as

$$Q_o = Q_{sv} - Q_{bh} \tag{21}$$

Above a circular lysimeter of radius r,

$$Q_{sv} = \pi r^2(\alpha k_w) \tag{22}$$

The lysimeter-induced lateral flow in the height interval dz can be approximated by

$$dQ_{bh} \simeq (-\alpha k_w/\rho_w g)\{(p_v - p_w)/r\}\ (2\pi r dz) \tag{23}$$

from Darcy's Equation. The radial pressure gradient has been taken to be something like $(p_v - p_w)/r$ where p_v is the undisturbed pressure in the surrounding snow and p_w is the pressure above the interface at height z. Integrating from the rim height z_r to $z = \infty$ and substituting into Equation 21 gives

$$C_v \approx 1 - (2/\rho_w g)(p_v/r)^2 \int_{p_r/p_v}^{1} (1 - x)/(1 - x^\eta)dx \tag{24}$$

after a variable change to $x = (p_w/p_v)$. $p_w = p_r$ at $z = z_r$.

For $z_r = \Delta z$, the integral takes the value $+ 6.4 \times 10^{-4}$ and $- 5.5 \times 10^{-4}$ for zero-tension and tension lysimeters, respectively, for $\eta = 13$ snow. The installation-hysteresis effect can be included in C_v by using the appropriate values for η and p_v from Figure 2 in Equation 24. The proximity of C_v to unity for properly constructed lysimeters is seen in Table 4.

TABLE 4

COLLECTION COEFFICIENT FOR LYSIMETERS WHOSE RIM HEIGHT EQUALS THE PRESSURE-GRADIENT ZONE THICKNESS ($\eta = 13$)

SCALED FLUX ($-V_{sv}/\alpha k_s$)	IGNORING HYSTERESIS EFFECT ($\tau_b = 300\ Nm^{-2}$)	INCLUDING HYSTERESIS EFFECT (Figure 2)
$p_i = 0$		
1.0×10^{-5}	0.99969	0.99096
20.1×10^{-5}	0.99980	0.99980
$p_i = -\infty$		
1.0×10^{-5}	1.00027	1.00076
20.1×10^{-5}	1.00017	1.000182

The relatively low rim required for eliminating the lysimeter-induced pressure disturbance, was given in the third column of Table 3. Too high a rim results in unnecessary disturbance to the overlying snow and its pattern of flow. The very short rim required for a tension lysimeter makes it especially useful in experiments requiring proximity between it and other snow instruments.

SUMMARY

Hydraulic effects of snow lysimeters are derived from porous media theory in terms of the zero-tension lysimeter, where the pervious lysimeter base is maintained at zero water pressure and which has been installed in a uniform ripe snowpack. The device is compared with the tension lysimeter with a lysimeter base pressure of $-\infty$.

1. The start-up time for the zero-tension lysimeter following installation in a snowpack varies from 4 hours to 3 days for input fluxes between 1.0×10^{-6} and 0.05×10^{-6} ms^{-1}, respectively.

2. The start-up time for the tension lysimeter is two orders of magnitude less.

3. The dynamic response of zero-tension lysimeters can be adequate for measurement of wetting front travel times if the instrument depth is large.

4. The flow-collection coefficient is essentially unity when the lysimeter has been provided with a raised rim whose height equals that of the pressure-gradient zone associated with the smallest flow to be measured.

5. The pressure gradient zone thickness above the lysimeter interface varies from 0.07 to 0.18 m for a zero-tension lysimeter and from 0.02 to 0.04 m for a tension lysimeter during diurnal melt cycles.

6. Installation-hysteresis has a significant effect on the pressure-gradient zone thickness.

NOTATION

A_L	lysimeter interface area, m^2
a	coefficient in the $k_w(p_w)$ relation, Nm^{-2}
b	exponent in the $k_w(p_w)$ relation
C_m	melt-collection coefficient
C_v	flow-collection coefficient
D_L	lysimeter depth below the surface, m
f_d	disturbance-melt factor
f_f	snow-melt transfer factor
g	acceleration of gravity, 9.80 ms^{-1}
k_s	intrinsic permeability, m^2
k_w	permeability to the liquid, m^2
P_a	absolute air pressure, Nm^{-2}
P_w	absolute water pressure, Nm^{-2}
p_i	interface water pressure, Nm^{-2}
p_r	water pressure at height z_r, Nm^{-2}
p_v	gravity-flow pressure, Nm^{-2}
p_w	snow-water pressure ($p_w = P_w - P_a$), Nm^{-2}
p_1, p_2	water pressure at heights z_1 and z_2
Q_{bh}	lysimeter-induced lateral flow, m^3s^{-1}
Q_{bv}	lysimeter base discharge, m^3s^{-1}
Q_c	percolate chamber discharge, m^3s^{-1}
Q_m	undisturbed net snow melt above lysimeter, m^3s^{-1}
Q_m	disturbed net snow melt above lysimeter, m^3s^{-1}
Q_o	lysimeter outlet discharge, m^3s^{-1}
Q_{sh}	lateral flow along icy layers, m^3s^{-1}
Q_{sv}	flow at lysimeter depth (in the absence of the base unit), m^3s^{-1}
r	lysimeter radius, m

S^*	effective saturation
S_v^*	gravity-flow effective saturation
t_d	dynamic response time, s
t_s	lysimeter start-up time, s
U	translatory wave speed, ms^{-1}
V	volume flux, positive upwards, ms^{-1}
V_{sv}	input flux to the lysimeter base (= Q_{sv}/A_L), ms^{-1}
V_0	initial flux, ms^{-1}
V_1	final flux, ms^{-1}
W_b	lysimeter-base storage, m^3
W_o	percolate collector and conduct storage, m^3
W_s	snow-water storage, m^3
w_b	lysimeter-base storage per unit area (W_b/A_L), m
x	integration variable (p_w/p_v)
z	height above a datum, m
z_r	lysimeter rim height, m
Δz	pressure-gradient zone thickness, m
α	5.47×10^6 $m^{-1}s^{-1}$ at 0.0°C ($\rho_w g/\mu_w$)
ε	pore size distribution index for $K_w(S^*)$
Θ	liquid water content by volume
Θ_0	initial liquid water content
Θ_1	final liquid water content
Θ_i	irreducible liquid water content
η	pore size distribution index for $k_w(p_w)$
μ_w	absolute viscosity of water, 1.79×10^3 kg $m^{-1}s^{-1}$ at 0.0°C
ρ_w	density of water, 1000 kg m^{-3} at 0.0°C
τ_b	bubbling suction, Nm^{-2}
ϕ	snow porosity.

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