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ABSTRACT

The present work investigates the thermal effect of a crude oil layer under fresh-water ice whose surface is superimposed by heat radiation. Experiments were carried out in a cold room at -15°C with oil thickness, ice thickness and radiation intensity as variables. It was found that the oil affected the linearity of the temperature profile, reduced the ice growth and decreased the loss in sensible heat of the ice. The radiation intensity affected the curvature of the ice temperature profile as well as the loss in sensible heat. However, neither the oil nor the ice thickness was found to have any unusual effect on the thermal behaviour of an oiled ice.

RESUME

The présent ouvrage étudie l'effet thermique d'une couche d'huile brute gisant sous une couche de glace d'eau douce dont la surface est surimposée de rayonnement thermique. Des expériences ont été effectuées dans une chambre froide à -15°C, et l'épaisseur de la couche d'huile, l' épaisseur de la glace et l'intensité du rayonnement ont servi de variables. On a constaté que l'huile influait sur la linéarité du profil de la température, réduisait la croissance de la glace et diminuait la perte de chaleur sensible de la glace. On a découvert en outre que l'intensité du rayonnement influait sur l'incurvation du profil de température de la glace, de même que sur la perte de chaleur sensible. Cependant, d'après les constatations, ni l'huile ni la couche de glace n'a d'effet extraordinaire sur le comportement thermique de la glace recouvrant une couche d'huile.

INTRODUCTION

Information on the thermal effect of an oil layer under ice is needed for assessing the environmental impact of an oil spill in ice-covered waters. In a previous publication[1], the thermal behaviour of an oil lens under fresh-water ice was reported. It was found that the oil, sandwiched in the ice, acted as an insulating layer impeding the flow of heat. The finding is in accord with those of Wolfe and Hoult[2] in their study of oil under artificial sea ice. For the case where the direction of heat flow is from water to the air, the ice temperature above the oil lens was found to be lower than the temperature at a corresponding point in the clean ice. In addition, the temperature profile across the oiled ice, instead of being a continuous straight line, as in the case for the clean ice, was found to break into two lines, respectively, for the ice above and below the oil. These experiments were conducted in a cold room without imposing any radiation on the ice.

In a practical case, the ice will be exposed to solar radiation. A fraction of the radiation energy may penetrate the upper ice layer and reach the oil underneath[3] and that may change the thermal behaviour of an oiled ice. An investigation on this is, therefore, worth attempting.

As a result of the insulating effect, an oil layer under ice is expected to reduce the ice growth rate during the ice formation period. However, in a field test conducted by NORCOR[4], no significant difference in thickness was found in ice containing oil in the experimental area and in clean ice in the control area. It is uncertain whether the difference was not detectable due to natural varations in ice thickness or that the oil layer was thick enough to cause free convection within the oil thus compensating the decrease in heat conduction. Laboratory tests under controlled experimental conditions are, therefore, required to clarify as to what extent that an oil layer of certain thickness retards the growth of ice.

The present work is a laboratory study on the thermal effect of a crude oil layer under artificially prepared fresh-water ice whose surface is under heat radiation.

EXPERIMENTAL DETAILS

Experiments were carried out in a cold room at $-15^{\circ} \pm 2^{\circ}C$. An aluminum tank, 150 cm I.D. and 70 cm deep with heating tapes and 10 cm polystyrene insulation on the outside wall, was installed in the cold room. The arrangements of heating tapes and insulation on the wall were to simulate a one-dimensional freezing[1]. The tank was divided by polystyrene plates (covered with plastic sheets) into two halves with one half being used as a control. Two thermistor probes were placed, respectively, in both halves of the tank for measuring the ice temperature profiles.

The tank was filled with water to a height of 60 cm. When the ice grew to the desired thickness, a pre-calculated amount of oil was injected from the bottom into the test half of the tank forming an oil layer of known thickness. Two identical radiation sources (250-watt sun lamps)were then placed, respectively, 50 cm above the ice surface in both halves of the tank. The radiation intensity was regulated by a variable transformer and was measured by a radiometer (YSI Model 65A). It was noted that before the oil was injected, the ice in both halves of the tank were at the same temperature. However, after injecting the oil and allowing it to form an equilibrium layer under the ice, temperatures of the ice above the oil layer dropped considerably; the ice temperature in the experimental half of the tank was a few degrees lower than the corresponding ice temperature in the control area when the radiant heat started. As ice was growing continuously, temperature profiles across the oiled ice as well as the clean ice and the total ice thickness in both sides of the tank were measured. The total ice thickness was determined daily by looking through the viewing window and reading on the measuring stick placed inside the tank. The ice growth rate was obtained by averaging the daily ice growth during a seven day period. The experimental set-up is shown schematically in Figure 1.

The variables studied were oil thickness (1.6 cm and 1.2 cm), ice thickness above the oil layer (15 cm, 10 cm and 8 cm), and the intensity of radiation on the ice surface (60 W/m^2 and 80 W/m^2). Norman Well crude oil was used in this investigation. Its physical properties are given in Table 1.

RESULTS AND DISCUSSION

Experimental ice temperature profiles are shown in Figures 2, 3, 4 and 5 where the vertical distance downward from the ice-air interface, L, is plotted against the ice temperature, T. Figure 2 shows the temperature profiles as a function of time, t, while Figures 3, 4 and 5 display, respectively, the effect of oil thickness, h_o, ice thickness, h_i, and radiation intensity, I. It is seen from these figures that all temperature profiles across a clean ice layer remain linear. However, ice temperature profiles above the oil layer deviate from a straight line, indicating that radiation does cause the oiled ice to alter somewhat its thermal behaviour.

The thermal condition of an ice layer depends upon the energy balance across the system; an equation may be written as follows:

$$Q_s = Q_r + Q_1 - Q_2 \qquad (1)$$

where Q_r is the rate of absorption of radiation. Q_1 and Q_2 are, respectively, the rate of heat flow in and out of the system. Q_s is the rate of storage or loss of sensible heat in the system as indicated by the rise or fall in temperature and is given by:

$$Q_s = \rho_i C_i \int_0^{L_i} \frac{\partial T}{\partial t}\, dL \qquad (2)$$

where ρ_i and C_i are, respectively, density and specific heat of the ice, $(\partial T/\partial t)$ is the rate of change in ice temperature and L_i is thickness of the ice layer.

From Figure 2, it is seen that the ice is losing sensible heat to the air as indicated by a fall in the temperature. The loss of sensible heat for a given value of L_i may be calculated from Equation (2). Referring to Figure 2, for a radiation intensity of 60 W/m², the average values of $\Delta T/\Delta t$ for the oiled ice and the clean ice are, respectively -0.10°C/day and -0.24°C/day. If the density and specific heat of the ice are taken[6] as 0.917 g/cm³ and 0.5 cal/g-°C, the values of Q_s with L_i = 10 cm for the oiled and clean ice are, respectively, -0.46 cal/cm²-day and -1.10 cal/cm²-day. Similarily, for I = 80 W/m², the values of Q_s for the oiled ice and the clean ice are -0.32 cal/cm²-day and -0.73 cal/cm²-day. (corresponding to an average $\Delta T/\Delta t$ value of -0.07°C/day and -0.16°C/day). The loss of sensible heat for the oiled ice, as is seen from here, amounts to only about 40% of that of a clean ice under the same condition.

The amount of heat lost from water is equal to the latent heat of ice formation, Q_h, which is given by:

$$Q_h = \rho_i \alpha \frac{dh_i}{dt} \qquad (3)$$

where α is the heat of freezing and (dh_i/dt) is the rate of change in ice thickness.

The value of Q_h may be calculated from the average ice growth rate, $\Delta h_i/\Delta t$. Experimental data for $\Delta h_i/\Delta t$ as well as the calculated values of Q_h are given in Table 2. It is seen that the ice growth rate, and therefore the value of Q_h, of an oiled ice is consistently smaller than that of a clean ice under the same environmental condition. The reduction in $\Delta h_i/\Delta t$ and thus in Q_h is about 35%. Experimental error in the measurement of Δh_i may be as high as 10%. The effects of l, h_o and h_i on the value of Q_h under the present experimental conditions are not detectable. To calculate other quantities in Equation (1) requires a considerable number of parameters and initial data that are not known with sufficient accuracy.

The reduction in $\Delta h_i/\Delta t$, confirms the insultating effect of the oil. As thermal conductivity of the ice is known to be much higher than that of the oil, a crude oil layer sandwiched in the ice should significantly decrease the conduction of heat through the system, and thus reduce the latent heat storage, Q_h. However, when a fluid is enclosed between two horizontal plane walls with its upper surface being at a lower temperature than the lower one, free convection may begin to occur if the product of the Grashof and Prandtl numbers is greater than seventeen hundred[7]. Using data given in Table 1, the Grashof number (Gr) and the Prandtl number (Pr) for the crude studied may be calculated as follows:

$$Gr = g\beta h_o^3 \Delta T_o/\nu^2 = 28.3\ h_o^3 \Delta T_o \qquad (4)$$

$$Pr = C_o \mu/k = 205 \qquad (5)$$

where g = gravitational constant, 980 cm/s

β = coefficient of thermal expansion of the oil, $^{o}C^{-1}$

ΔT_o = temperature difference across the oil layer, ^{o}C

ν = kinematic viscosity of the oil, stokes

C_o = specific heat of the oil, cal/g-^{o}C

μ = viscosity of the oil, poise

k = thermal conductivity of the oil, cal/cm-^{o}C-s

The product of Gr and Pr is, therefore,

$$(Gr \times Pr) = 5802\ h_o^3\ \Delta T_o \qquad (6)$$

When a crude oil is allowed to spread under an ice cover, the equilibrium thickness of the slick will likely be around 1 cm[1,2,4]. According to Equation (6), free convection will occur within the oil layer for such an oil thickness even when ΔT_o is as small as 0.3^{o}C. For oil thicknesses of 1.2 cm and 1.6 cm, the product of Gr and Pr will be greater than 1700 if the values of ΔT_o are, respectively, greater than 0.2^{o}C and 0.1 ^{o}C. The actual values of ΔT_o were not measured in this investigation. However, the temperature difference across the oil layer, ΔT_o, is expected to be greater than 0.2^{o}C and some free convective currents are believed to exist in the oil. The convective heat transfer within the oil layer will increase as the thickness of the oil increases. The insulating effect of an oil layer may diminish if the increase in convection compensates the decrease in conduction.

From Figure 3, it is seen that the ice temperature above an oil layer of 1.6 cm thick is lower than the corresponding ice temperature above a 1.2 cm oil layer. This indicates that an increase in h_o from 1.2 cm to 1.6 cm does not eliminate the insulating effect of the oil layer.

The change in the ice thickness above the oil (h_i) has no unusual thermal effect on the oiled ice as is seen from Figure 4; the decrease in T due to an increase in h_i is a normal phenomenon since an increase in h_i enhances the resistance to heat flow.

The effect of radiation intensity on the ice temperature profile may be seen in Figure 5 where data from a previous investigation [1] for zero intensity (I = 0) are included for comparison. As is seen from this figure, temperatures of the ice with an oil layer underneath are lower than the temperature at a corresponding point in the clean ice. Moreover, as the intensity, I, increases, this difference in temperature between the oiled ice and the clean ice decreases (e.g., at L = 1 cm, the differences in ice temperature between the oiled ice and the clean ice are, respectively, 4°C, 1.6°C and 1.1°C for I = 0, 60 W/m² and 80 W/m²), while the curvature of the temperature profile of the oiled ice slightly increases as the intensity, I, increases.

As mentioned earlier, radiation energy may penetrate through an ice layer and reach the oil underneath. The fraction of transmission through the ice depends on the ice preoperties and the wavelength of the radiation. However, most of the radiation reaching the oil surface will be absorbed by the oil since the oil transmits very little radiation[4, 8]. In the meantime, all the long wavelength back radiation emitted by the oil surface will be absorbed by the ice above the oil because the ice is opaque to long wavelength radiation[9]. An ice layer above an oil lens will, therefore, absorb more radiation than a clean ice layer under the same condition. This explains the decrease in difference between temperatures of the oiled ice and temperatures of the clean ice at a corresponding point. It is thought also to be responsible for the reduction in the loss of sensible heat and the non-linear behaviour of the ice temperature profile.

CONCLUSIONS AND POTENTIAL APPLICATIONS

Based on the results obtained, the following conclusions may be made concerning a crude oil layer under fresh-water ice with heat radiation being superimposed on the ice surface:

(1) Although some convective currents are believed to exist within the oil, a crude oil layer of around 1.5 cm thick reduces the total flow of heat across the ice and, hence, lowers the ice growth rate during the ice formation period. The oil also reduces the loss of sensible heat from the ice to the air. For an ice thickness (above the oil layer) of about 10 cm and a radiation intensity of between 60 and 80 W/m^2 (measured on the ice surface), the reductions in ice growth rate and in the loss of sensible heat are, respectively, 35% and 40%.

(2) The radiation superimposed on the ice surface affects the thermal behaviour of an oiled ice; the ice temperature profile above the oil layer is no longer linear and the difference between the ice temperature with an oil layer underneath and the corresponding temperature of a clean ice becomes smaller as the radiation intensity increases.

(3) Under the experimental conditions of this investigation, the oil thickness and the ice thickness above the oil have no significant effect on the thermal behaviour of the system other than increasing the resistance to the thermal conduction.

Any difference in the properties of an oiled ice and a clean ice offers a potential method for detecting oil spilled under ice. The finding of this investigation, namely, that in the presence of radiation, the clean ice loses more sensible heat to the air than does the ice with an oil layer underneath, may be a possible means for remote sensing of oil slicks under ice. Moreover, if during winter months, oiled ice loses less sensible heat (i.e., cooling down at a slower rate), a logical extension of this is that during spring or summer months when the direction of heat flow is from the air to the water and the intensity of solar radiation is at its peak period, oiled ice will gain more sensible heat (i.e., warming up quicker) than does a clean ice, therefore, leading to an earlier melting of the contaminated ice. The earlier melting of oil-contaminated ice, which has been, in fact, confirmed by field experiments[4], will create oil pools where the oil is effectively contained by the surrounding uncontaminated ice; it appears that the cleanup of an under ice oil spill after the melting of the spill area is, therefore, desirable from a strategy point of view. Other findings of this investigation regarding the behaviour of an oiled ice, such as the non-linearity of temperature profile and the reduction in ice growth, may also be a useful input for assessing the effect of a sub-ice oil spill.

ACKNOWLEDGEMENTS

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NOMENCLATURE

C_i	= specific heat of ice, cal/g-^{o}C
C_o	= specific heat of oil, cal/g-^{o}C
d	= differential operator
Gr	= Grashof number, dimensionless
g	= gravitational constant, 980 cm/s^2
h_i	= thickness of ice, cm
h_o	= thickness of oil, cm
I	= radiation intensity, W/m^2
k	= thermal conductivity of oil, cal/cm-^{o}C-s
L	= vertical distance downward from the ice-air interface, cm
Pr	= Prandtl number, dimensionless
Q_h	= latent heat storage of ice, cal/cm^2-day
Q_1	= rate of heat flow in the system, cal/cm^2-day
Q_2	= rate of heat flow out of the system, cal/cm^2-day
Q_r	= rate of absorption of radiation, cal/cm^2-day
Q_s	= storage or loss of sensible heat in the ice, cal/cm^2-day
T	= ice temperature, ^{o}C
t	= time, day
$\Delta h_i/\Delta t$	= average ice growth rate, cm/day
$\Delta T/\Delta t$	= average rate of change in ice temperature, ^{o}C/day
ΔT_o	= temperature difference across the oil layer, ^{o}C
α	= latent heat of freezing, 79.7 cal/g
β	= coefficient of thermal expansion of the oil, $^{o}C^{-1}$
μ	= viscosity of the oil, poise
ν	= kinematic viscosity of the oil, stokes
ρ_i	= density of the ice, g/cm
∂	= partial differential operator

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Table 1. Physical Properties of Norman Well Crude Oil

Pour point	-50°C
Colour	dark green
Degree API at 15°C	38.4
Density at 0°C	0.85 g/cm
Viscosity at 0°C	0.15 poise
* Specific heat at 0°C	0.41 cal/g-°C
* Thermal conductivity at 0°C	3 x 10⁻ cal/cm-°C-s
* Coefficient of thermal expansion at 0°C	9 x 10⁻ °C^{-1}

* Data from Reference (5)

Table 2. Experimental Data for Ice Growth Rate and Calculated Values of Q_h

			Ice Growth Rate, cm/day		Q_h, cal/cm^2-day	
I, W/m^2	h_i, cm	h_o, cm	Oiled Ice	Clean Ice	Oiled Ice	Clean Ice
80	10	1.2	0.44	0.71	32.2	51.9
80	10	1.6	0.43	0.70	31.4	51.2
60	10	1.2	0.73	1.10	53.4	80.4
60	10	1.6	0.76	1.12	55.5	81.9
60	8	1.6	0.97	1.27	70.9	92.8
60	15	1.6	0.58	1.00	42.4	73.1

Figure I

Schematic Diagram of the Experimental Set-up

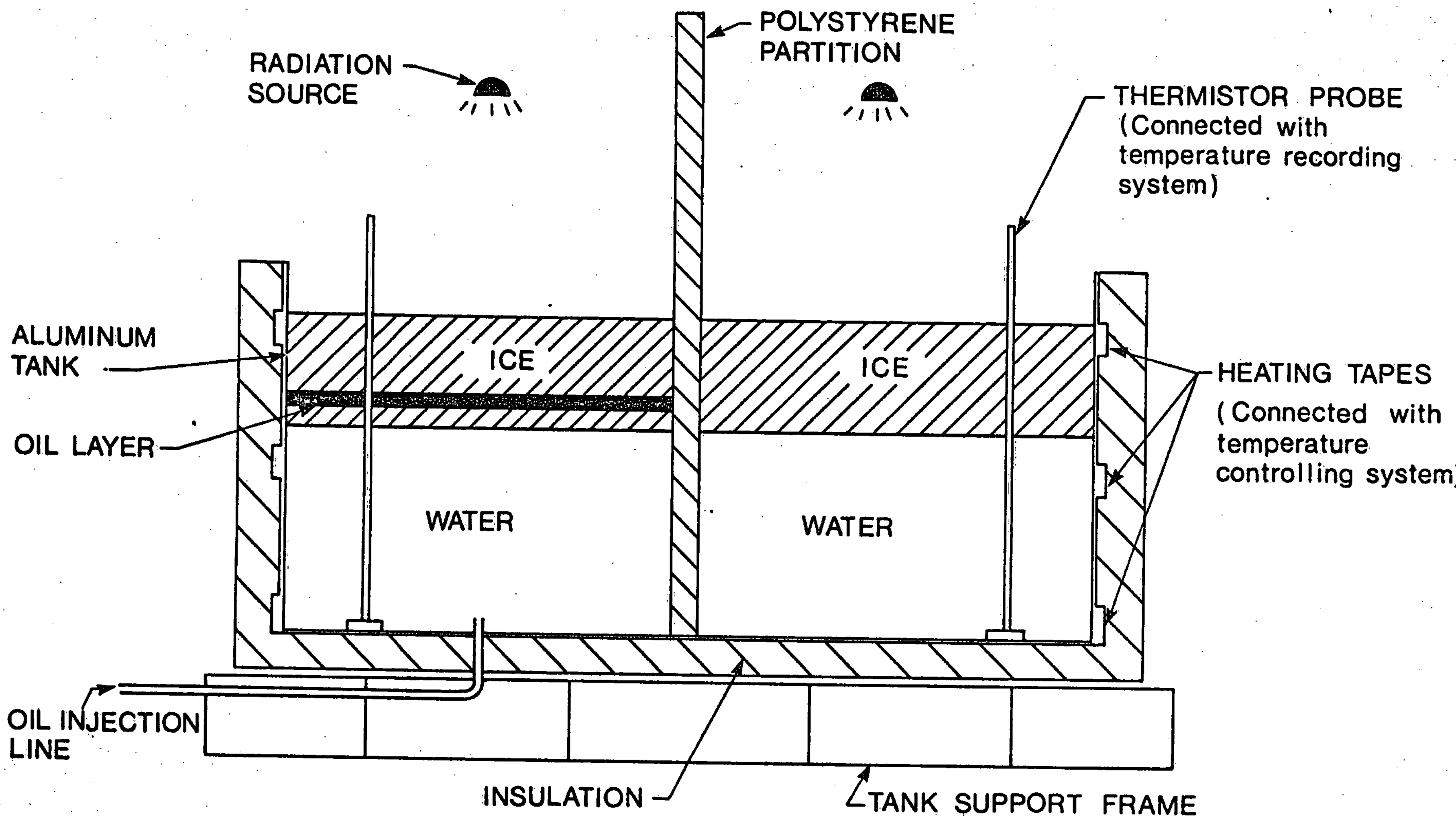
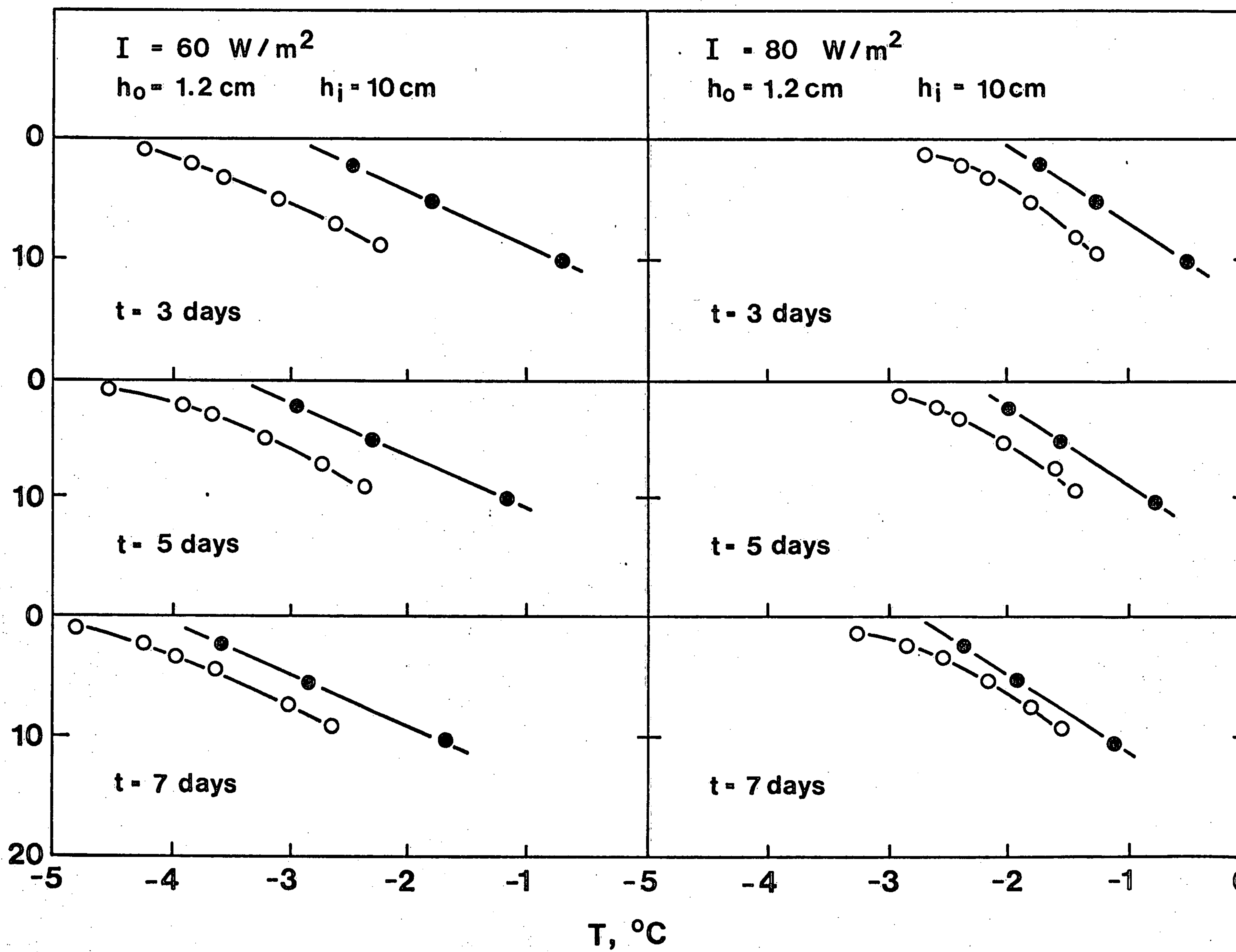

POLYSTYRENE
PARTITION
RADIATION
SOURCE
THERMISTOR PROBE
(Connected with
temperature recording
system)
ALUMINUM
TANK
ICE
ICE
HEATING TAPES
(Connected with
temperature
controlling system)
OIL LAYER
WATER
WATER
OIL INJECTION
LINE
INSULATION
TANK SUPPORT FRAME

Figure 2

Ice Temperature Profile as a Function of Time

● - for clean ice in the control area
o - for oiled ice in the experimental area

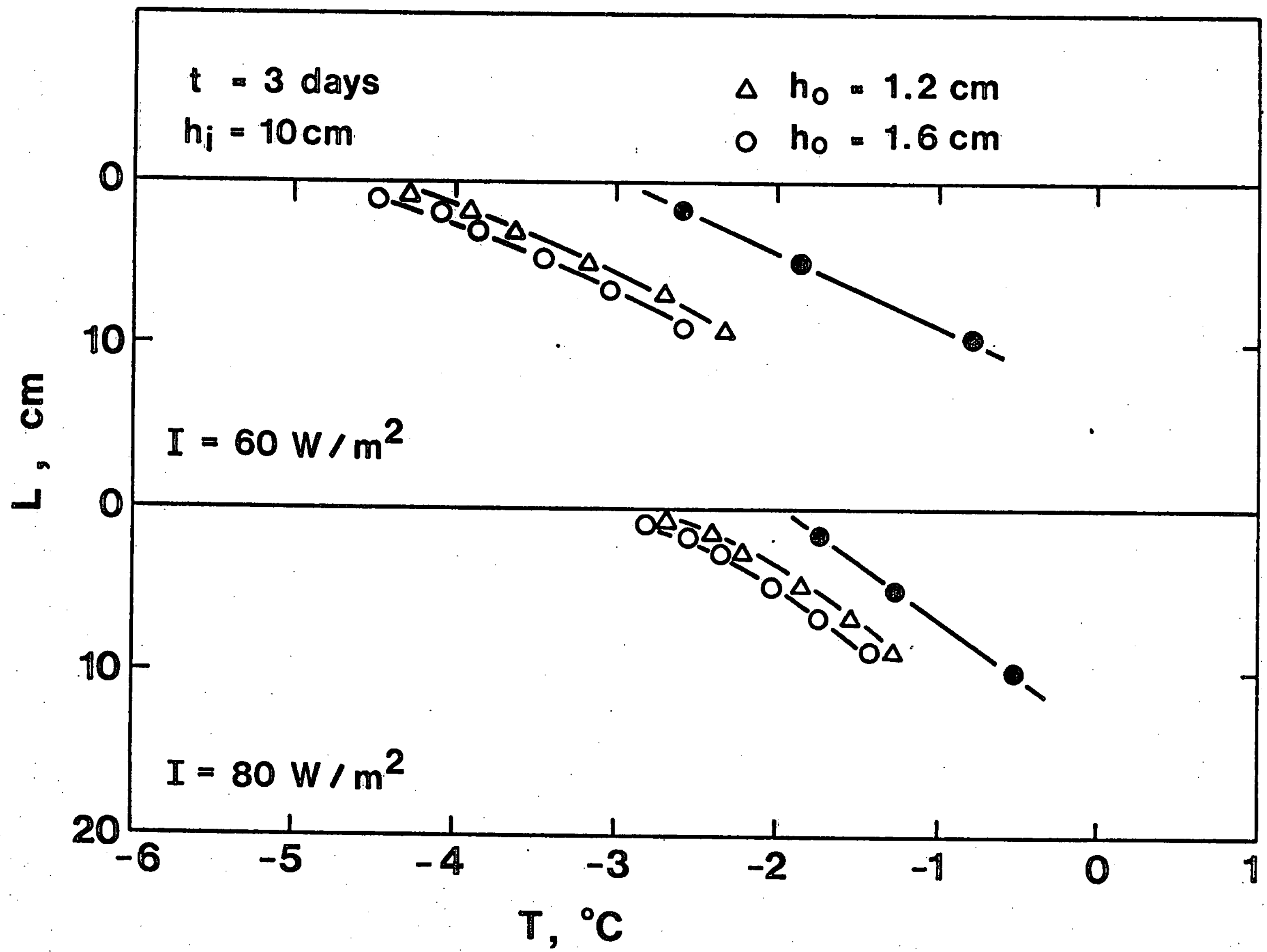


I = 60 W/m2
ho = 1.2 cm
hi = 10 cm
I = 80 W/m2
ho = 1.2 cm
hi = 10 cm
t = 3 days
t = 5 days
t = 7 days
t = 3 days
t = 5 days
t = 7 days
0
10
0
10
0
10
20
L, cm
-5
-4
-3
-2
-1
-5
-4
-3
-2
-1
0
T, °C

Figure 3

Effect of Oil Thickness on the Temperature Profile

● - for clean ice in the control area
o - for oiled ice in the experimental area

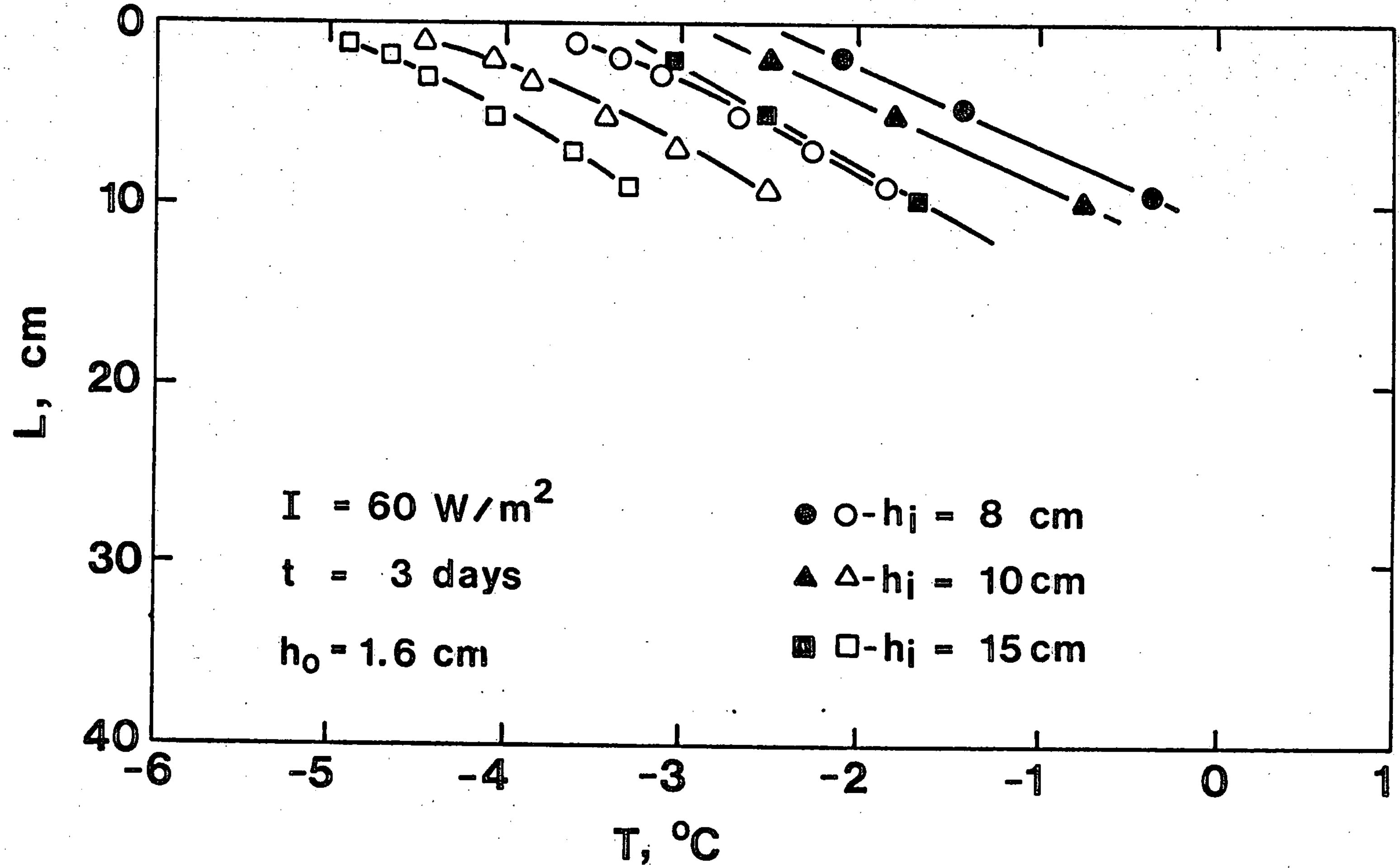


t = 3 days
h$_i$ = 10 cm
△ h$_o$ = 1.2 cm
○ h$_o$ = 1.6 cm
I = 60 W/m^2
I = 80 W/m^2
L , cm
T, °C
0
10
0
10
20
-6
-5
-4
-3
-2
-1
0
1

Figure 4

Effect of Ice Thickness on the Temperature Profile

● - for clean ice in the control area
o - for oiled ice in the experimental area

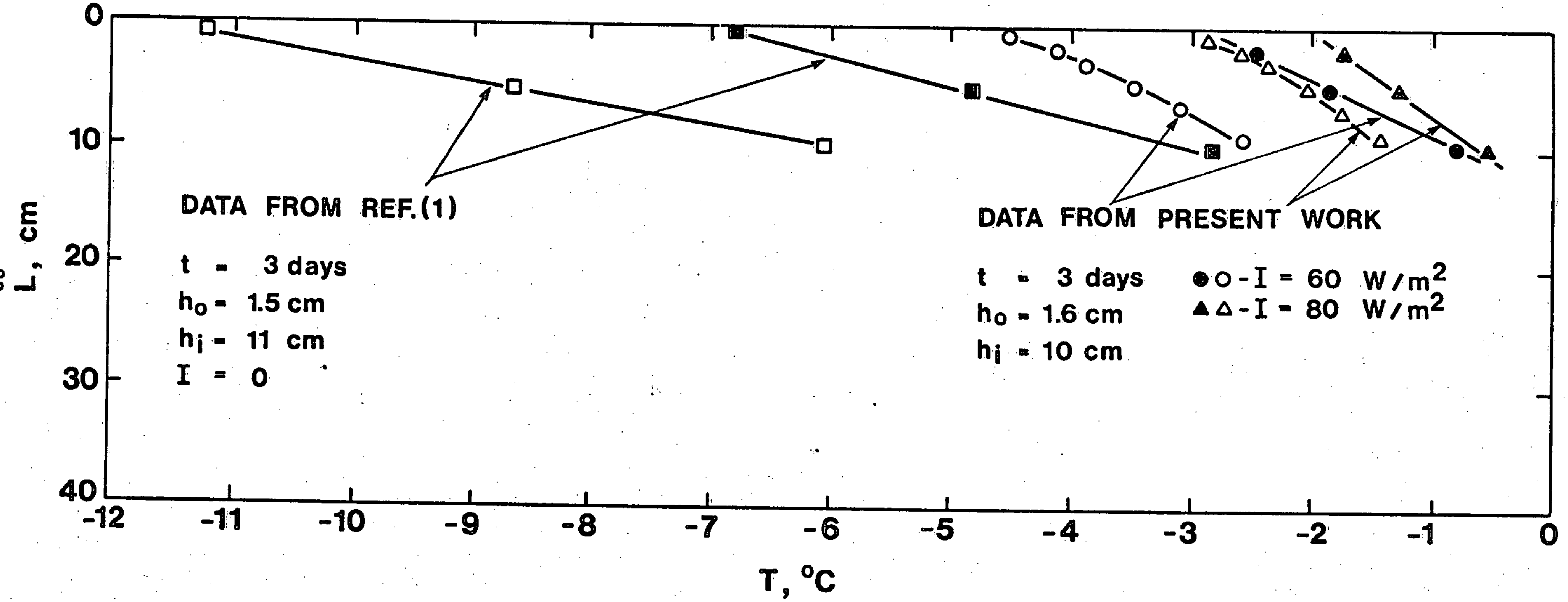


L, cm
T, °C
I = 60 W/m²
t = 3 days
h_o = 1.6 cm
● ○ - h_i = 8 cm
▲ △ - h_i = 10 cm
■ □ - h_i = 15 cm

Figure 5

Effect of Radiation Intensity on the Temperature Profile

● - for clean ice in the control area
o - for oiled ice in the experimental area



DATA FROM REF.(1)
t = 3 days
h₀ = 1.5 cm
hᵢ = 11 cm
I = 0
DATA FROM PRESENT WORK
t = 3 days
h₀ = 1.6 cm
hᵢ = 10 cm
●○ - I = 60 W/m²
▲△ - I = 80 W/m²
L, cm
T, °C