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Energy Transport in Porous Insulator Systems

A. L. Berlad, N. Tutu, R. Jaung and Y-J. Yeh
Energy Technology Laboratory
Mechanical Engineering Department
State University of New York at Stony Brook
Long Island, New York 11794

Part Of
The National Program
For
Building Thermal Envelope Systems and Insulating Materials

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Buildings Division

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INTERIM PROGRESS REPORT ON AN INVESTIGATION OF ENERGY TRANSPORT IN POROUS INSULATOR SYSTEMS

A. L. Berlad, N. Tutu, R. Jaung, and Y-J. Yeh

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FOREWORD

This is one of a series of reports to be published describing research, development, and demonstration activities in support of the National Program for Building Thermal Envelope Systems and Insulating Materials. The National Program involves several federal agencies and many other organizations in the public and private sectors who are addressing the national objective of decreasing energy wastes in the heating and cooling of buildings. Results described in this report are part of the National Program through delegation of management responsibilities for the DOE lead role to the Oak Ridge National Laboratory.

Other reports in this series include the following which are available from NTIS.

1. DOE/CS-0059: The National Program Plan for Building Thermal Envelope Systems and Insulating Materials (January 1979).

2. ORNL/SUB-7556/I: Assessment of the Corrosiveness of Cellulosic Insulating Materials (June 1979).

3. ORNL/SUB-7504/3: Recessed Light Fixture Test Facility (July 1979).

4. ORNL/SUB-7559/I: Problems Associated with the Use of Urea-Formaldehyde Foam for Residential Insulation (September 1979).

Ted S. Lundy
Program Manager
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and Insulating Materials

E. C. Freeman
Program Manager
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Department of Energy

Abstract

An exploratory investigation of various air intrusion as well as other energy transport effects on porous insulator systems has been carried out at SUNY, Stony Brook. The results of the four-month investigation show quantitatively that there are a number of significant, commonly encountered, air intrusion situations which can substantially degrade the thermal performance of building thermal barriers and the conditioned spaces that they serve.

Acknowledgment

The authors are grateful to the Oak Ridge National Laboratory and the U. S. Department of Energy for support of this investigation under ORNL Subcontract No. 7551.

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I. INTRODUCTION AND BACKGROUND

The thermal resistance (R-value) of a permeable insulating material is generally determined in test apparatuses designed to prohibit external air intrusion into the test sample. Substantial care is also taken to consider samples subjected to one-dimensional heat transfer processes. Such measured R-values are then generally employed to characterize the effective thermal resistance of an *in situ* insulation system. Inasmuch as the selected insulating material is the major insulating component of the insulation system, standard calculational procedures[1] predict system thermal resistances which are dominated by the laboratory determined R-values.

It is significant to note that such laboratory-determined R-values are associated with steady-state test methods/apparatuses which exclude the following processes:

(a) forced air intrusion into or about the test sample

(b) forced air intrusion into and through the test sample

(c) air flows within the test sample which are induced by (forced) air flows in the neighborhood of the test sample

(d) diffusive water vapor flow

(e) forced convection of moist air.

Nevertheless, realistic, installed insulation systems may sustain one or more of the aforementioned processes. It is well-known from the established heat and mass transfer literature (e.g., Ref. 2-5) that

processes such as (a)-(e), above, may substantially alter the heat transfer characteristics of a permeable thermal barrier.

Accordingly, the research reported herein examines the applicability of (normally given) R-values of permeable insulation materials to systems wherein air intrusion effects may be physically possible. Several kinds of findings are investigated.

(a) Laboratory determined R-values for several types and thicknesses of permeable insulators, under conditions of no externally imposed flows

(b) Laboratory determined heat transfer rates for several permeable insulators under conditions of externally imposed flows (air intrusion)

(c) Theoretically calculated heat transfer rates for permeable insulation systems which sustain infiltrative-exfiltrative air intrusion effects.

Additionally, for some low density, permeable insulators, natural convection within the volume may be suppressed by impermeable boundaries which define a "thin" sample of insulator. For "thick", permeable, low density insulators, widely-separated impermeable boundaries may be ineffective in suppressing natural convection. If such is the case, the R-value per unit length of a given "thick" permeable insulator may be smaller than that of a corresponding "thin" sample. Where the insulation sample is also transmissive in the infrared regime, increasing thickness tends to suppress infrared losses, thereby counteracting natural convective loss increases. Thus, the work reported herein attempts to determine

experimentally the existence-nonexistence of natural convection in selected permeable insulation systems. It also examines, experimentally, the effect of air intrusion on a permeable insulation system that is sealed on all sides but one. For the case of an insulation system which sustains infiltrative-exfiltrative flows, an analysis is presented which shows that the classic use of R-values, taken in conjunction with a presumably separable "infiltrative loss" is generally inadequate to specification of the system's heat loss rates.

II. EXPERIMENTAL STUDIES

A number of different experimental apparatuses were employed in order to address a series of separate issues.

(a) Existence/Nonexistence of Free Convection:

The first apparatus (Figure 1) was employed to examine the existence/nonexistence of free convective effects within the body of a permeable insulation system. In this experiment, a permeable glass fiber batt was vertically situated between parallel warm and cold boundaries. Extensive, fine thermocouple arrays were employed to determine the horizontal temperature profiles within the body of the glass fiber batt at three different heights. For a glass fiber batt density of 6.41 kg/m^3 the temperature fields shown in Figures 2 and 3 are obtained. Figure 2 is for a total temperature difference of 33.3^oK. Figure 3 is for a total temperature difference of 73.9^oK. In each case, the dashed (straight) line corresponds to the pure conductive case. The solid curve is drawn through the temperature data for the lowest of the three planes.

(b) Air Intrusion Effects for a Glass Wool Batt:

A second apparatus (Figure 4) was employed to examine the effects of two different kinds of air intrusion on a sample of a permeable insulator which is sealed on five of its six sides. Three cases corresponding to an insulator heated from below, and open to room air at its top surface, were studied. For the

apparatus and experiments of Figure 4, observed temperature fields are shown for the case of no imposed flow-field, for the case of a free stream flow of air at 1.3 m/s (4.5 ft/s) parallel to the open surface, and for the case of a free stream flow of air at 3.0 m/s (10 ft/s) at 45° with the horizontal.

(c) R-Values for Several Permeable Insulators:

A third apparatus was employed to examine the R-values of several fully sealed samples of permeable insulators, in order to determine possible natural convective/radiative effects for the case where outside air intrusion is not possible. This apparatus employs a 0.610 m by 0.610 m heat transfer gauge, in series with a test sample of similar size. Both heat transfer gauge and test sample are situated between steady, warm and cold boundaries and virtually thermally isolated in the transverse direction. This apparatus has been previously described and was employed in the studies of reference (6). Figure 5 shows the measured R-value per unit thickness for two different types of sealed, permeable, optically thick insulators. Figure 6 shows the measured R-value per unit thickness for a selected sealed, permeable, optically non-thick insulator.

Discussion of Experimental Results

Data obtained and shown in Figures 2-5, inclusive,

clearly indicate that natural convection in sealed, permeable insulators can occur and that natural convection as well as air-intrusion into partially-sealed, permeable insulators can degrade the effective R-value of a permeable insulator. Thus, for example, the nonlinear temperature profiles in Figures 2 and 3 illustrate the characteristic occurrence of free convection in a sealed permeable insulator system.

Figure 4 data show the manner in which heat loss rates through partially sealed permeable insulators can occur, even for very low air intrusion rates. In the experiment of Figure 4 it is interesting to note that the steady state temperature of the heated copper plate varies from 50.1^{o}C for the "no imposed flow" case to 48.3^{o}C for the "horizontal flow" case to 45.1^{o}C for the "flow at 45°" case. Inasmuch as the rate of heating of the copper plate is the same for all three cases, it follows that the heat losses from the copper plate, through the permeable insulator above it is greatest for case (d) and least for case (a). This can be seen to imply that the "effective R-value" is least for case (d) and greatest for case (a). This can be further illustrated by an examination of the continuity condition at the copper plate. Let (k_1) be the effective conductivity of the impermeable insulator below the copper plate and (k_2) the effective conductivity of the permeable insulator above the copper plate. Then, at the copper plate

$$\left| k_1 \frac{dT_1}{dx} \right|_i + \left| k_2 \frac{dT_2}{dx} \right|_i = \dot{q}''$$

where $\dot{q}''$ is the steady, per unit area heat dissipation rate of the copper plate and the subscript i corresponds to the cases (a), (b), (d), respectively. $\dot{q}''$ is the same for all three cases. Inasmuch as (k) is the same for all three cases, it follows that

$$\left| k_1 \frac{dT_1}{dx} \right|_a > \left| k_1 \frac{dT_1}{dx} \right|_b > k_1 \left| \frac{dT_1}{dx} \right|_d$$

and it follows that

$$\left| k_2 \frac{dT_2}{dx} \right|_a < \left| k_2 \frac{dT_2}{dx} \right|_b < \left| k_2 \frac{dT_2}{dx} \right|_d$$

Thus, the effective R-value is least for case (d) and greatest for case (a). Further, the shape of the temperature profile for case (d) shows that $k_{2,d}$ is spatially nonuniform <u>and</u> that $k_{2,d}$ is larger in the neighborhood of the permeable boundary than in the neighborhood of the copper plate.

The experiments employing the heat transfer gauge test apparatus have been useful in identifying natural convective effects in several permeable insulators, for both optically thick and optically non-thick materials.

Results for a sample of 70 kg/m^3 cellulose and for 96 kg/m^3 vermiculite are shown in Figure 5. These two, sealed, permeable

insulators are optically thick and increasing the thickness of a sample under test does not significantly change the radiative contribution to the heat transfer rate. The R-value per unit thickness is degraded significantly as sample thickness is varied from 2.54 cm and to 15.24 cm; a six-fold change. Further, the results appear to indicate that thinner-than-tested samples would have higher R-values per unit thickness than those shown in Figure 5.

Results for a sample of loose glass fiber wool are shown in Figure 6. This low density material shows a minimum R-value in the neighborhood of 5 cms thickness. These observed data correspond to the complex interplay of a natural convective heat transfer component that increases, in going from less than 1 cm thickness to some 10 cm of thickness and a radiative transport component that decays exponentially as thickness is varied between 1 cm and some 10 cm.

III. ANALYSIS OF HEAT TRANSFER RATES FOR A SYSTEM OF INSULATORS WHICH SUSTAINS INFILTRATIVE-EXFILTRATIVE FLOWS

It is well known that a residential structure whose conditioned space sustains infiltrative-exfiltrative flows suffers heat losses over and above those assignable to conduction through its thermal barrier.

Where the thermal barrier itself is permeable and subject to infiltrative-exfiltrative flows, the effective R-values of the barrier are modified and the heat losses for the overall system have to be reconsidered. Thus, consider the case where a permeable insulating material has a cold boundary temperature $T_0 = 0$ and $x = 0$ and a hot boundary temperature T_δ at $x = \delta$. Take this permeable slab to sustain steady infiltrative (cold) flow from the cold boundary to the hot boundary. The governing energy conservation equation with flow is

$$\rho c_p u \frac{dT}{dx} = k \frac{d^2T}{dx^2} \tag{1}$$

where ρ = density of air, u = velocity of air, c_p = specific heat capacity, k = thermal conductivity of the medium.

Equation (1) has the solution

$$T_{inf} = T_0 + \left[\frac{T_\delta - T_0}{\exp\left(\frac{c_p G\delta}{k}\right) - 1}\right]\left\{\exp\left[\frac{c_p Gx}{k}\right] - 1\right\} \tag{2}$$

The heat transfer rates to the cold boundary are suppressed by this (counterflow) infiltrative flow. The effect of various flow rates has been calculated for the typical case where

$$c_p = 0.25 \text{ BTU/lb/}^{o}\text{F } (4183 \text{ j/kg}\cdot\text{K}),$$

$$k = 0.014 \text{ BTU/h}\cdot\text{ft}\cdot^{o}\text{F } (0.024 \text{ W/m}\cdot\text{K}),$$

$$\rho = 0.0807 \text{ lbs/ft}^3 \ (1.294 \text{ kg/m}^3),$$

$$\delta = 0.333 \text{ ft } (0.101 \text{ m}),$$

$$t_\delta = 68^{o}\text{F } (20^{o}\text{C}), \ t_0 = 0^{o}\text{F } (-17.78^{o}\text{C}).$$

The heat loss rate at x = 0 is proportional to (dT/dx) at x = 0 and is listed below for several flow rates (Figure 7).

u, (m/s)	0	8.47×10^{-5}	8.47×10^{-4}
$\left(\frac{dT}{dx}\right)_0, \ \left(\frac{^{o}C}{m}\right)$	372	288	14.8

Clearly, the suppression of the infiltrative heat loss rate tells an incomplete story. Within the heated space, there exists a heat release rate for the system. In practice this heat release rate is of such a magnitude as to provide a steady state for the overall infiltrative-exfiltrative system. Consider that the "warm wall" of the conditioned space is the exfiltrative wall and that it is permeable to the same flow as that previously examined. Let T_i = inside temperature of the warm wall which is located at x = s. Let T* = outside temperature of the warm wall which is located at x = s + δ. Then, in a similar manner, we find the temperature field within the exfiltrative wall to be

$$T_{exf.} = T_i - (T_i - T^*) \left\{ \frac{\exp\left[\frac{c_p G x}{k}\right] - 1}{\exp\left[\frac{c_p G \delta}{k}\right] - 1} \right\} \tag{3}$$

where $G = \rho u$ = mass flow rate. The corresponding conductive heat losses for the exfiltrative wall and for the infiltrative wall are given by

$$[\dot{q}''_{exf.}]_{s+\delta} = -\left\{ \frac{c_p G(T_i - T^*)}{\exp\left[\frac{c_p G \delta}{k}\right] - 1} \right\} \tag{4}$$

and

$$[\dot{q}''_{inf.}]_{\delta} = \left\{ \frac{c_p G(T_\delta - T_0)}{\exp\left[\frac{c_p G \delta}{k}\right] - 1} \right\} \tag{5}$$

The net convective loss for the system can be shown to be given by $[c_p G(T_i - T_0]$. Accordingly, the total heat loss through the system $(0 \leq x \leq s + \delta)$ is given by

$$-\dot{Q}''_s = \left\{ \frac{c_p G}{\exp\left[\frac{c_p G \delta}{k}\right] - 1} \right\} \left\{ (T_\delta - T_0) + (T_i - T^*) \right\} + c_p G(T_i - T_0). \tag{6}$$

In general, the system heat loss rate is increased as $G = \rho u$ varies from zero to large positive values. It can be shown that equation (6) implies a <u>purely convective</u> heat loss rate as $G = \rho u$ becomes very large. That is, for large G-values:

$$\dot{Q}''_s \rightarrow c_p G(T_i - T_0) \tag{7}$$

The generalized permeable insulator problem which includes the thermal coupling of an infiltrative regime (say regime A-B), a conditioned space which contains a heat source, $\dot{q}'''$, and sustains transverse losses (say regime B-C), and an exfiltrative regime (say regime C-D) is to be treated elsewhere. It may be characterized in terms of the coupled differential equations:

$$A \leq x \leq B: \quad \rho u c_p \left(\frac{dT}{dx}\right) = k_{AB} \left(\frac{d^2T}{dx^2}\right) \tag{8}$$

$$B \leq x \leq C: \quad \rho u c_p \left(\frac{dT}{dx}\right) = k_{BC} \left(\frac{d^2T}{dx^2}\right) + \dot{q}''' - L(T) \tag{9}$$

$$C \leq x \leq D: \quad \rho u c_p \left(\frac{dT}{dx}\right) = k_{CD} \left(\frac{d^2T}{dx^2}\right) \quad . \tag{10}$$

subject to the appropriate boundary and continuity conditions.

It is instructive to note the sensitivity of the "effective R-value" of an insulator when subjected to intrusive flow directly through its permeable interior. Figure 7 shows the temperature profiles [equation (2)] associated with infiltrative flow into a heated space, through a permeable insulator. For invariant boundary conditions, the infiltrative flow greatly suppresses the "conductive" loss to the cold, upstream boundary. Of course, the increased enthalpy of the infiltrative air has been supplied by the heated interior. Similarly, one may employ equation (3) to describe the temperature profiles on the exfiltrative side of the heated space.

For fixed boundary conditions on the exfiltrative insulator, Figure 8 shows the temperature profiles associated with flow rates of $u = 0$, $u = 8.47 \times 10^{-5}$ m/s (1 ft/hr), and $u = 8.47 \times 10^{-4}$ m/s (10 ft/hr), respectively. The "conductive" heat loss at the cold boundary is increased by the imposed flow. It can be shown by differentiation of equation (6) that $\dot{Q}''_s$ has a minimum.

For the more realistic case of a heated (conditioned) space which separates two permeable insulators--all of which sustains infiltrative-exfiltrative flow, Figure 9 shows the analytic model schematics which corresponds to equations (8)-(10). The nature of the temperature field is such as to reflect the relatively warm interior temperature on the exfiltrative wall and a relatively cool interior temperature on the infiltrative wall. Figure 10 compares the general features of the Figure 9 model for the cases of "no forced convection" and with forced convection. Inasmuch as $(\dot{q}''')$ is the same for both cases, the systems heat losses are the same. However, the maximum temperature achieved for the "no forced convection" case is substantially higher. That is, the "conditioned space" may be considered to be more comfortable.

It also follows that solution of equations (8)-(10) for the constraint that the conditioned space temperature maximum be the same for $(u_1 = 0)$ and for $(u_2 >> 0)$ implies the temperature structures of Figure 11. That is, the "drafty" condition associated with $u_2 >> 0$ requires that $\dot{q}''''_2 > \dot{q}''''_1$, in order for T_{max} to be the same for both

cases, Even for the same T_{max}, however, it is clear that the (u_1=0) case corresponds to a more comfortable interior than that for (u_2 >> 0).

IV. CONCLUSIONS

Intrusive air flows of several kinds can serve to degrade the insulating value of various permeable insulator systems. A permeable insulator which is sealed on all sides but one can have its effective R-value degraded by a forced convective coupling at its unsealed surface. Further, a system of two permeable insulators which bound a "conditioned space" and which sustains infiltrative/exfiltrative flow sustains heat loss rates which are <u>not</u> derivable from simple R-value considerations. Neither can such heat loss rates be determined from the addition of a simply calculated "conductive loss" to an estimated "infiltrative loss". Finally, it is also seen that perfectly sealed permeable insulators can have their effective R-values degraded by natural convective processes.

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VI. FIGURES

Figure Captions

Figure 1. Glass Fiber Batt Heated Along a Vertical Surface.

Figure 2. Measured Temperature Profiles (Figure 1 Experiment). $\Delta T = 33.3^{o}K$.

Figure 3. Measured Temperature Profiles (Figure 1 Experiment). $\Delta T = 73.9^{o}K$.

Figure 4. Air Intrusion Effects on Heat Transfer for a Glass Wool Batt.

Figure 5. Free Convective Effects on R-Values of Several Permeable Insulators (optically thick case).

Figure 6. Free Convective Effects on R-Values of a Permeable Insulator (optically non-thick case).

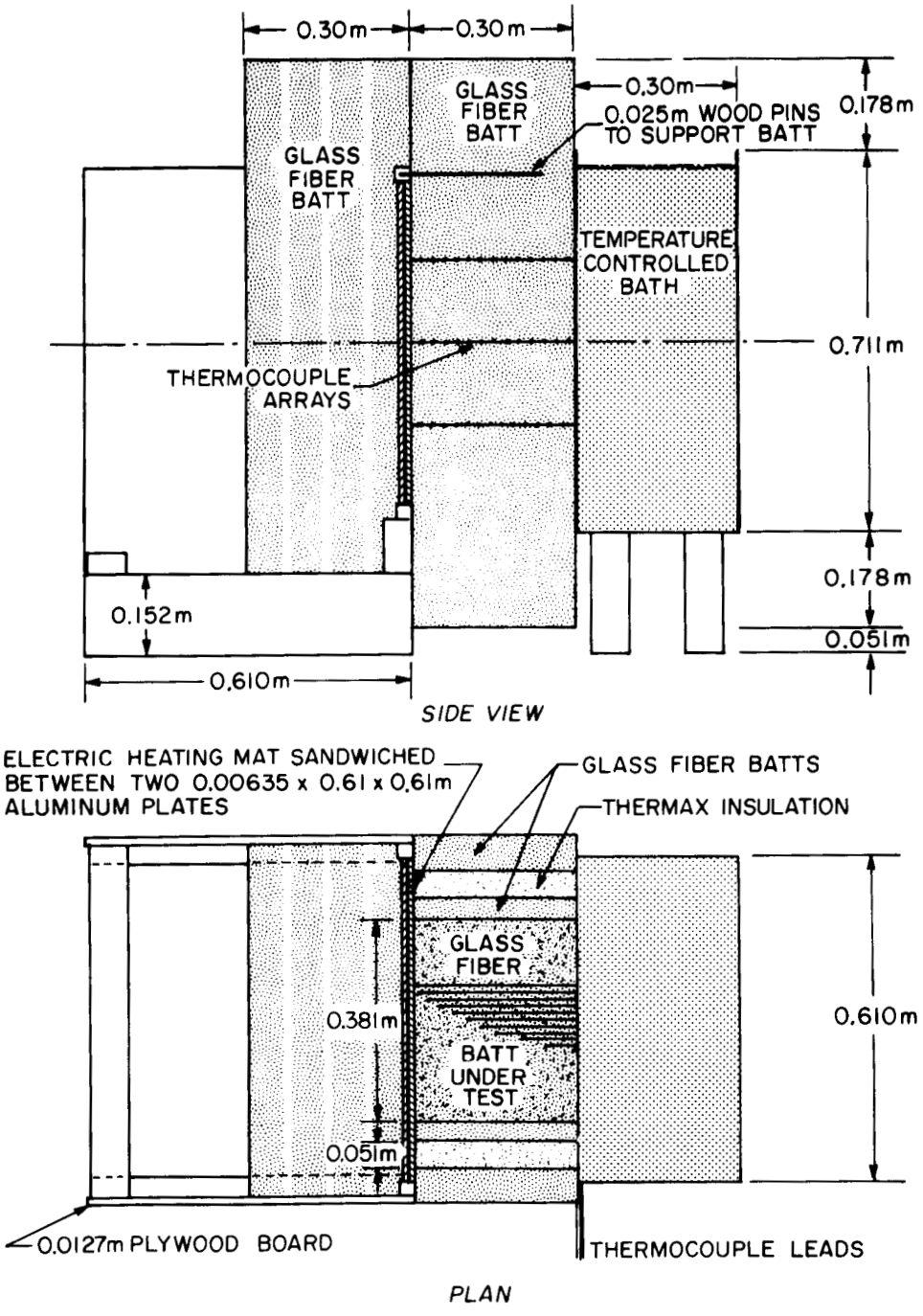
Figure 7. Infiltrative Temperature Profiles.

Figure 8. Exfiltrative Temperature Profiles.

Figure 9. Schematic of Infiltration + Heating + Exfiltration Sequence.

Figure 10. Comparative Heat Loss Mechanisms.

Figure 11. Temperature Profiles for a Fixed Maximum Interior Temperature, with and without Infiltrative/Exfiltrative Flow.



GLASS FIBER BATT HEATED ALONG A VERTICAL SURFACE

Fig. 1

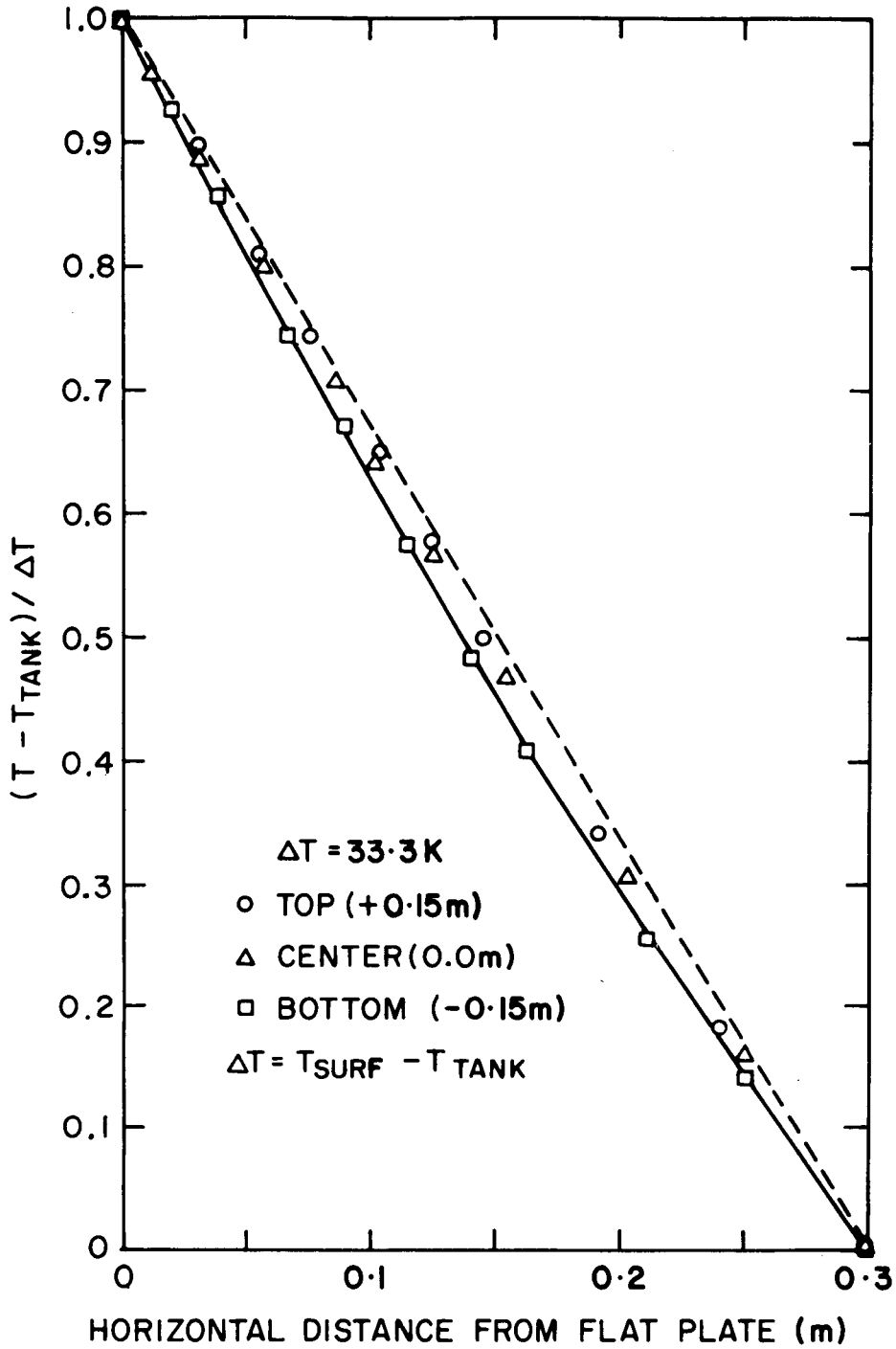

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
(T − T_TANK) / ΔT
ΔT = 33·3 K
TOP (+0·15m)
CENTER (0.0m)
BOTTOM (−0·15m)
ΔT = T_SURF − T_TANK
0
0·1
0·2
0·3
HORIZONTAL DISTANCE FROM FLAT PLATE (m)

Fig. 2

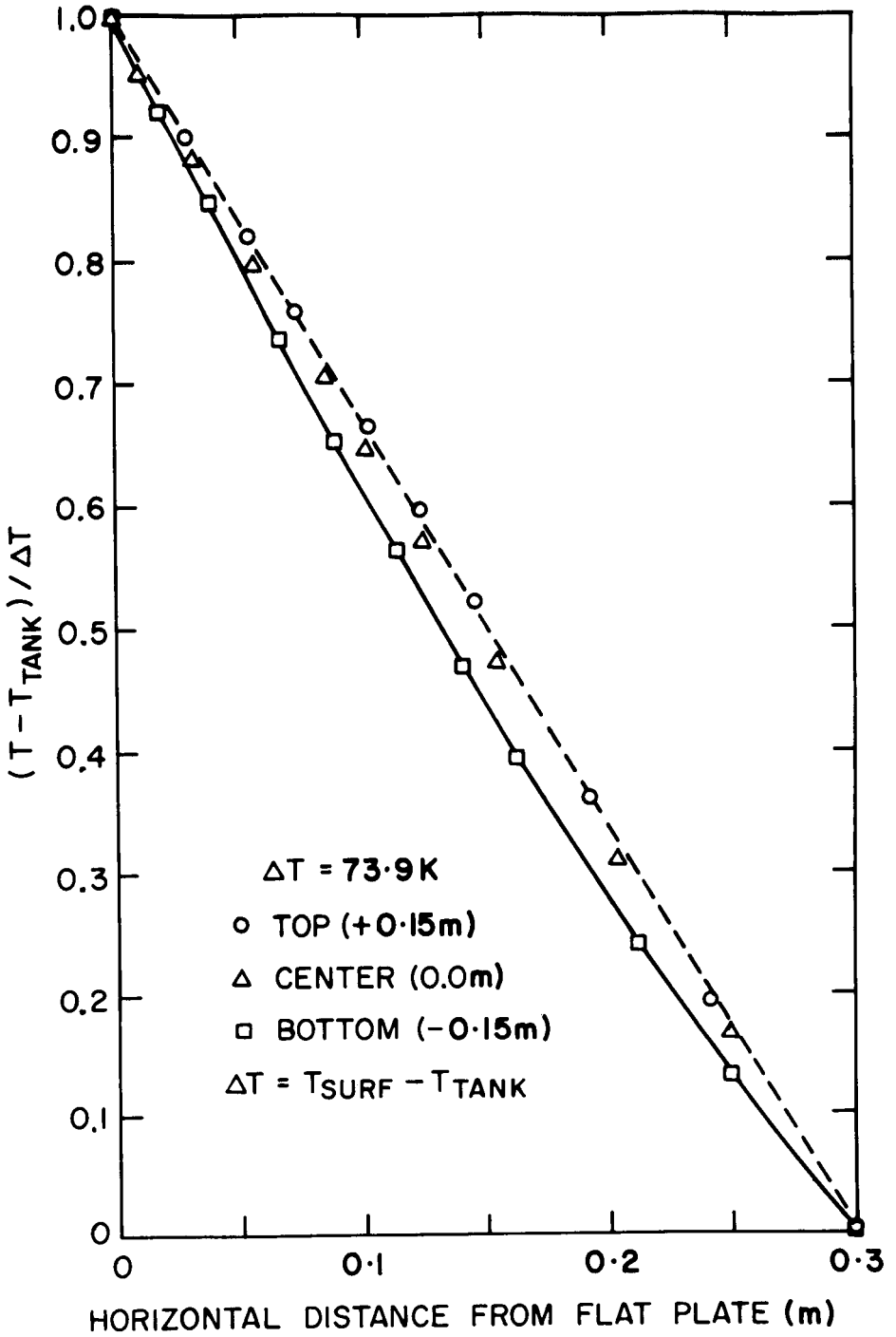

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
(T − T_TANK) / ΔT
ΔT = 73·9K
TOP (+0·15m)
CENTER (0.0m)
BOTTOM (−0·15m)
ΔT = T_SURF − T_TANK
0
0·1
0·2
0·3
HORIZONTAL DISTANCE FROM FLAT PLATE (m)

Fig. 3

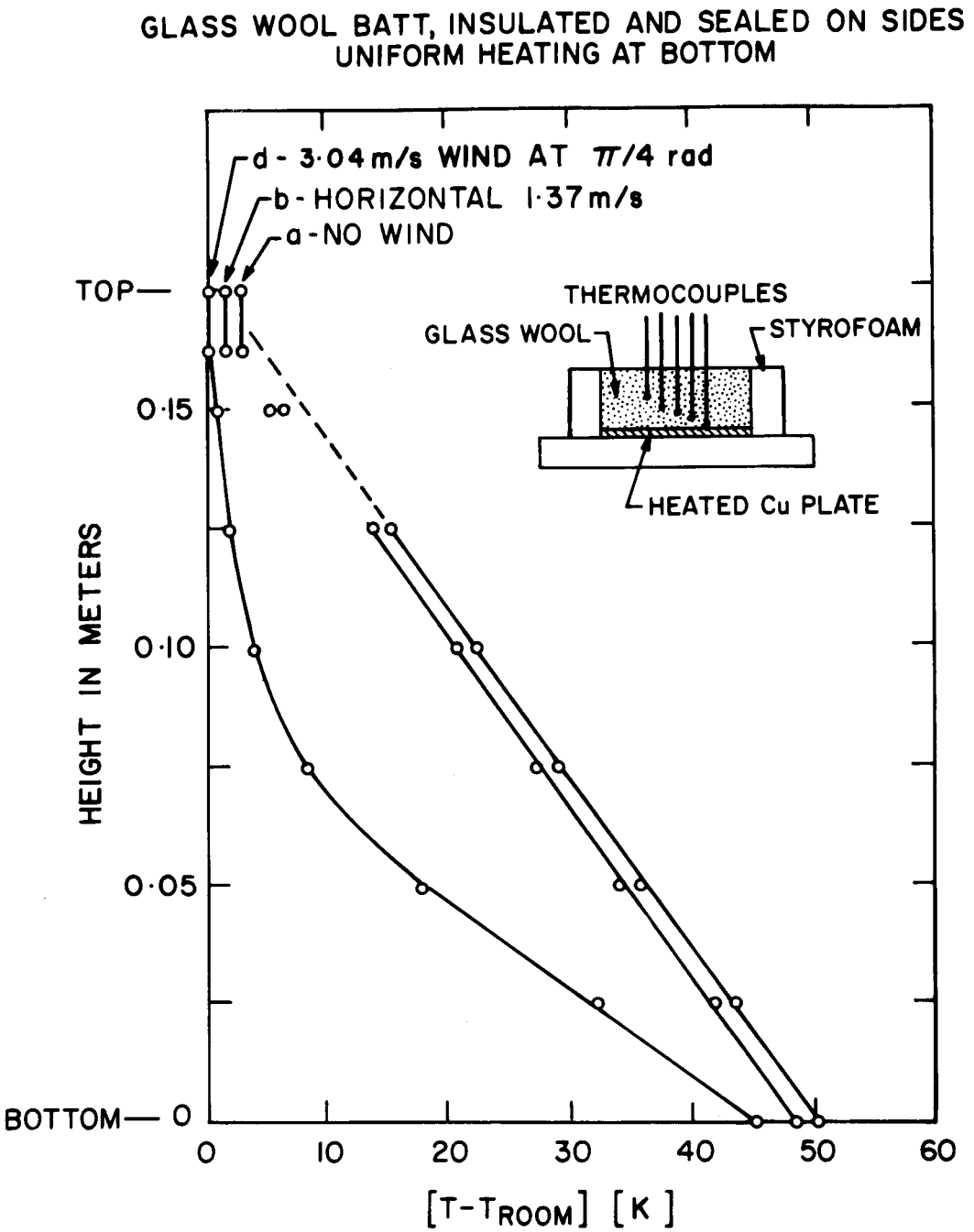
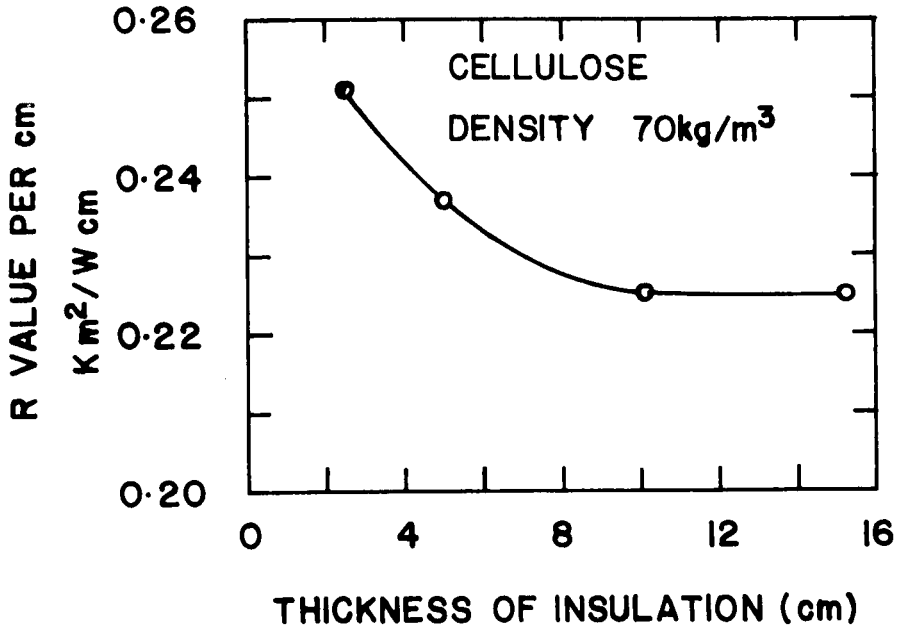

GLASS WOOL BATT, INSULATED AND SEALED ON SIDES
UNIFORM HEATING AT BOTTOM
d - 3·04 m/s WIND AT π/4 rad
b - HORIZONTAL 1·37 m/s
a - NO WIND
THERMOCOUPLES
GLASS WOOL
STYROFOAM
HEATED Cu PLATE
TOP
0·15
0·10
0·05
BOTTOM 0
HEIGHT IN METERS
0
10
20
30
40
50
60
[T-T ROOM] [K]

Fig. 4


0·26
0·24
0·22
0·20
R VALUE PER cm
K m²/W cm
CELLULOSE
DENSITY 70kg/m³
0
4
8
12
16
THICKNESS OF INSULATION (cm)

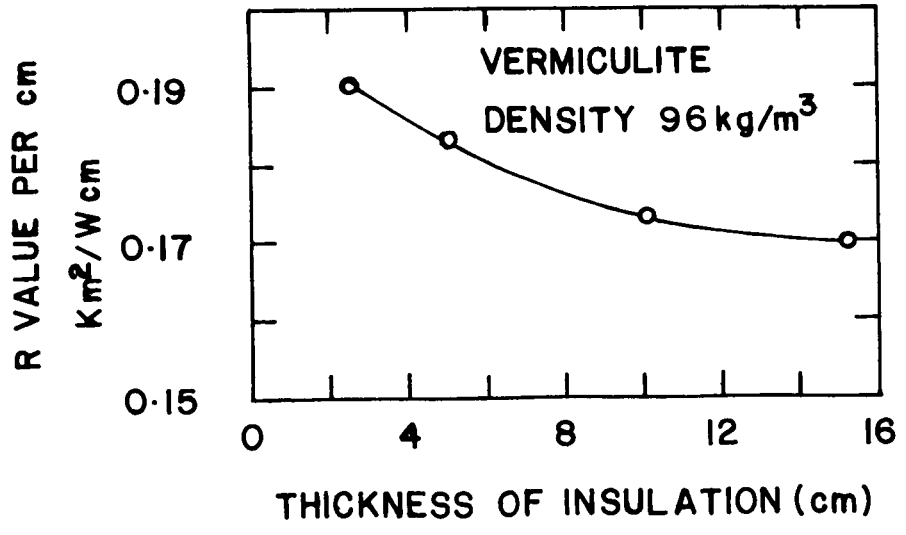

0·19
0·17
0·15
R VALUE PER cm
K m²/W cm
VERMICULITE
DENSITY 96 kg/m³
0
4
8
12
16
THICKNESS OF INSULATION (cm)

Fig. 5

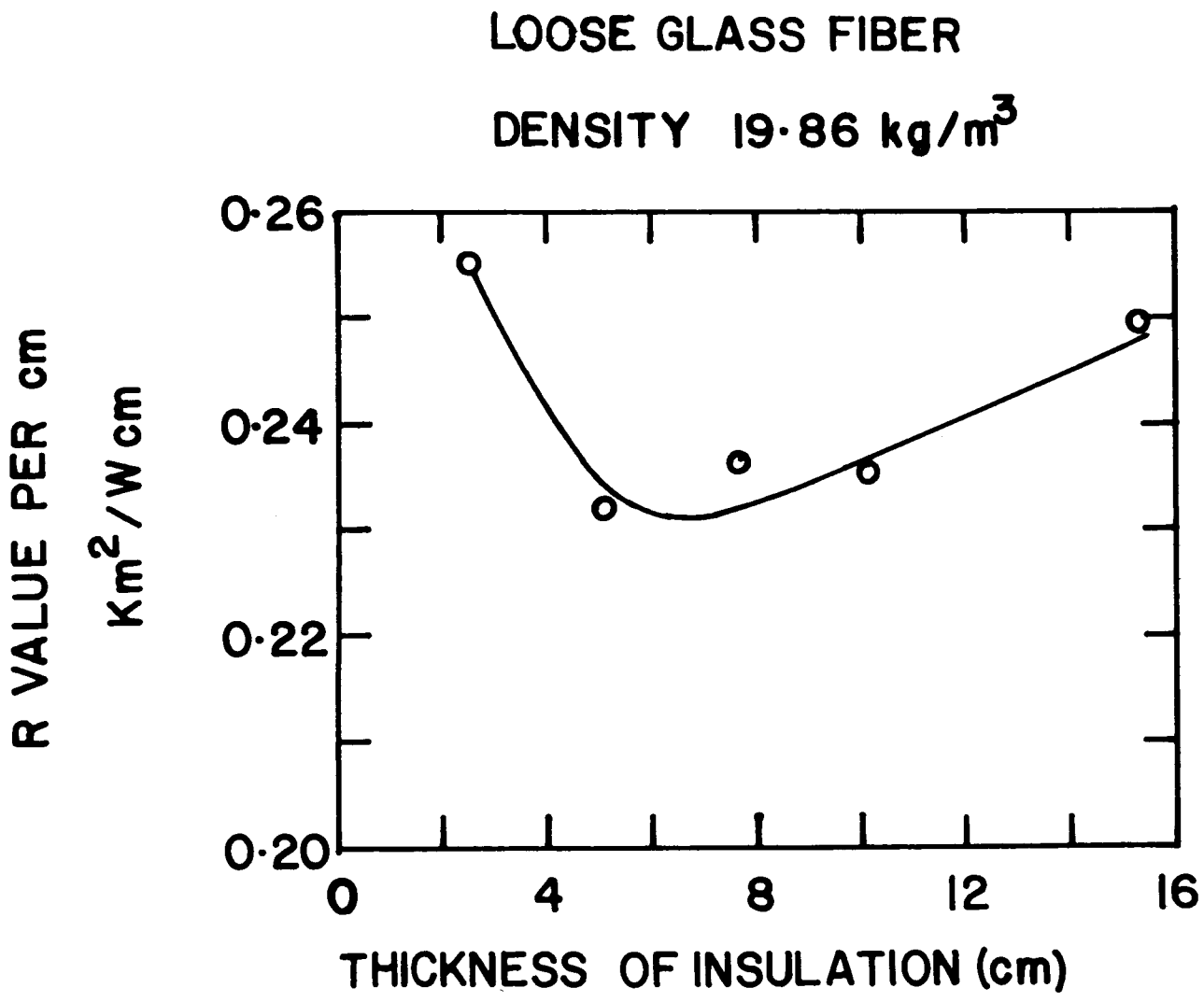

LOOSE GLASS FIBER
DENSITY 19·86 kg/m3
R VALUE PER cm
Km2/W cm
0·26
0·24
0·22
0·20
0
4
8
12
16
THICKNESS OF INSULATION (cm)

Fig. 6

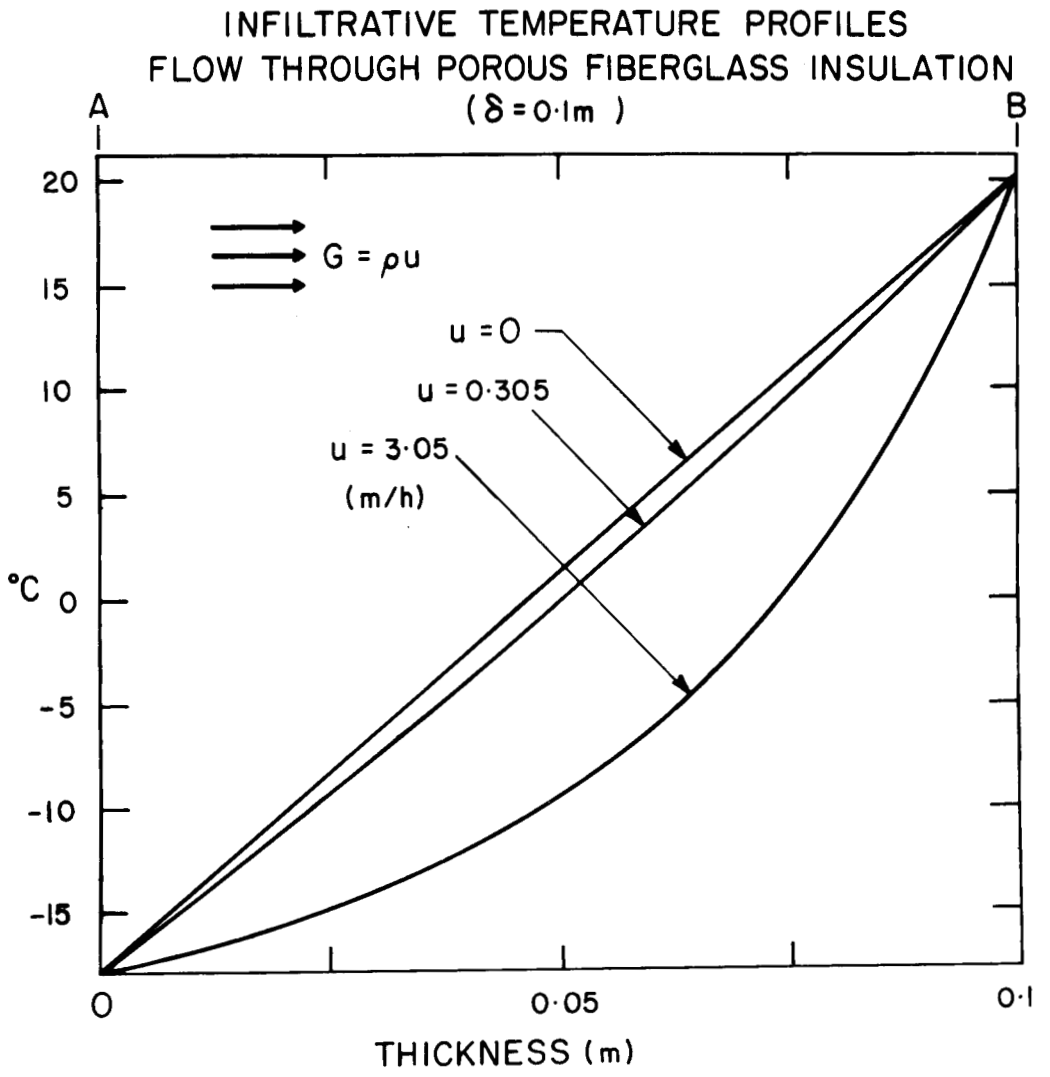

INFILTRATIVE TEMPERATURE PROFILES
FLOW THROUGH POROUS FIBERGLASS INSULATION
(δ = 0·1m)
A
B
20
15
10
5
°C 0
-5
-10
-15
G = ρu
u = 0
u = 0·305
u = 3·05
(m/h)
0
0·05
0·1
THICKNESS (m)

Fig. 7

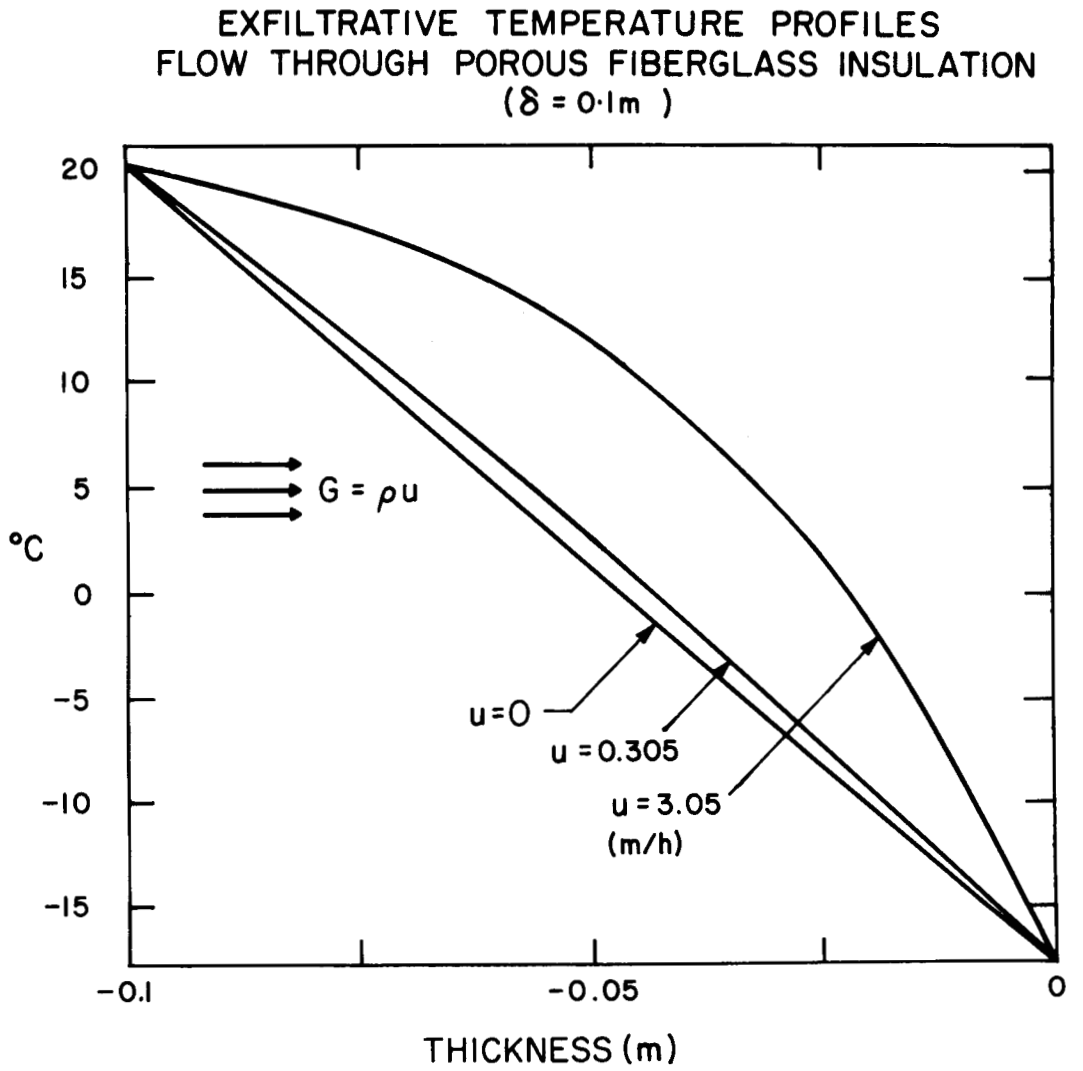

EXFILTRATIVE TEMPERATURE PROFILES
FLOW THROUGH POROUS FIBERGLASS INSULATION
(δ = 0·1m)
20
15
10
5
0
-5
-10
-15
°C
G = ρu
u=0
u = 0.305
u = 3.05
(m/h)
-0.1
-0.05
0
THICKNESS (m)

Fig. 8

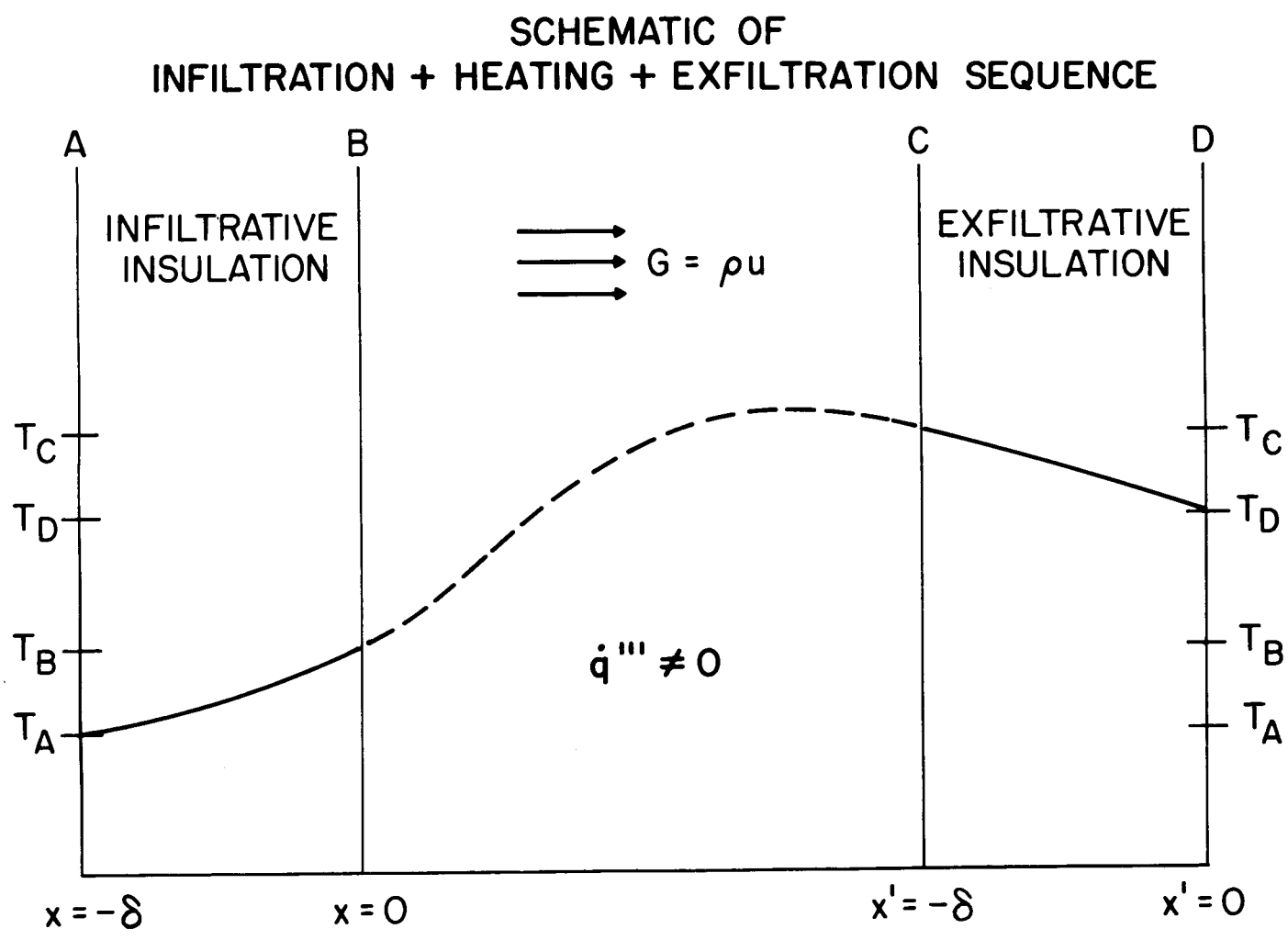

SCHEMATIC OF
INFILTRATION + HEATING + EXFILTRATION SEQUENCE
A
B
C
D
INFILTRATIVE INSULATION
G = ρu
EXFILTRATIVE INSULATION
T_C
T_D
T_B
T_A
$\dot{q}''' \neq 0$
T_C
T_D
T_B
T_A
x = −δ
x = 0
x' = −δ
x' = 0

Fig. 9

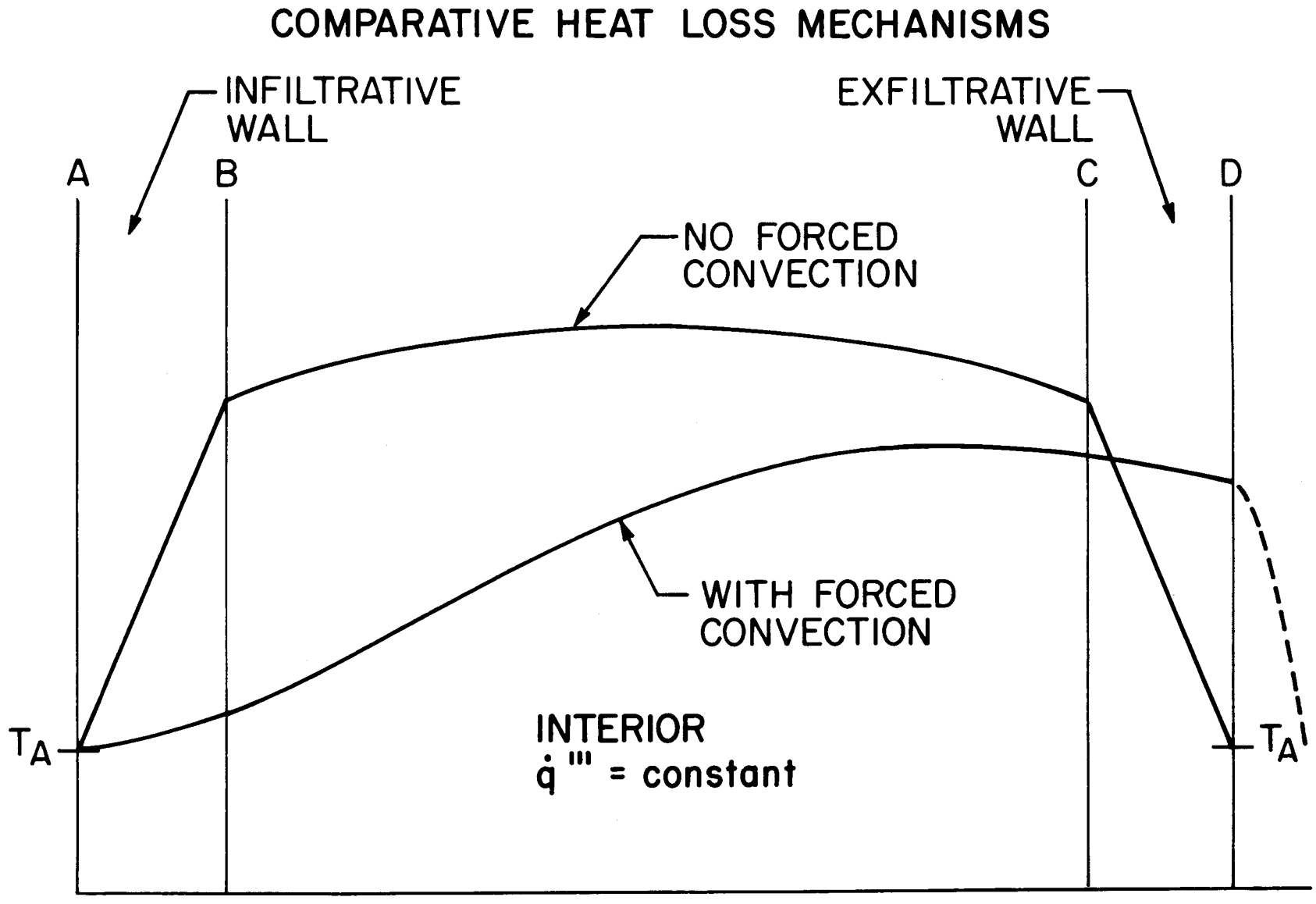

COMPARATIVE HEAT LOSS MECHANISMS
INFILTRATIVE WALL
EXFILTRATIVE WALL
A
B
C
D
NO FORCED CONVECTION
WITH FORCED CONVECTION
INTERIOR
$\dot{q}''' = \text{constant}$
T_A
T_A

Fig. 10

SCHEMATIC OF MODEL UNDER CONSIDERATION

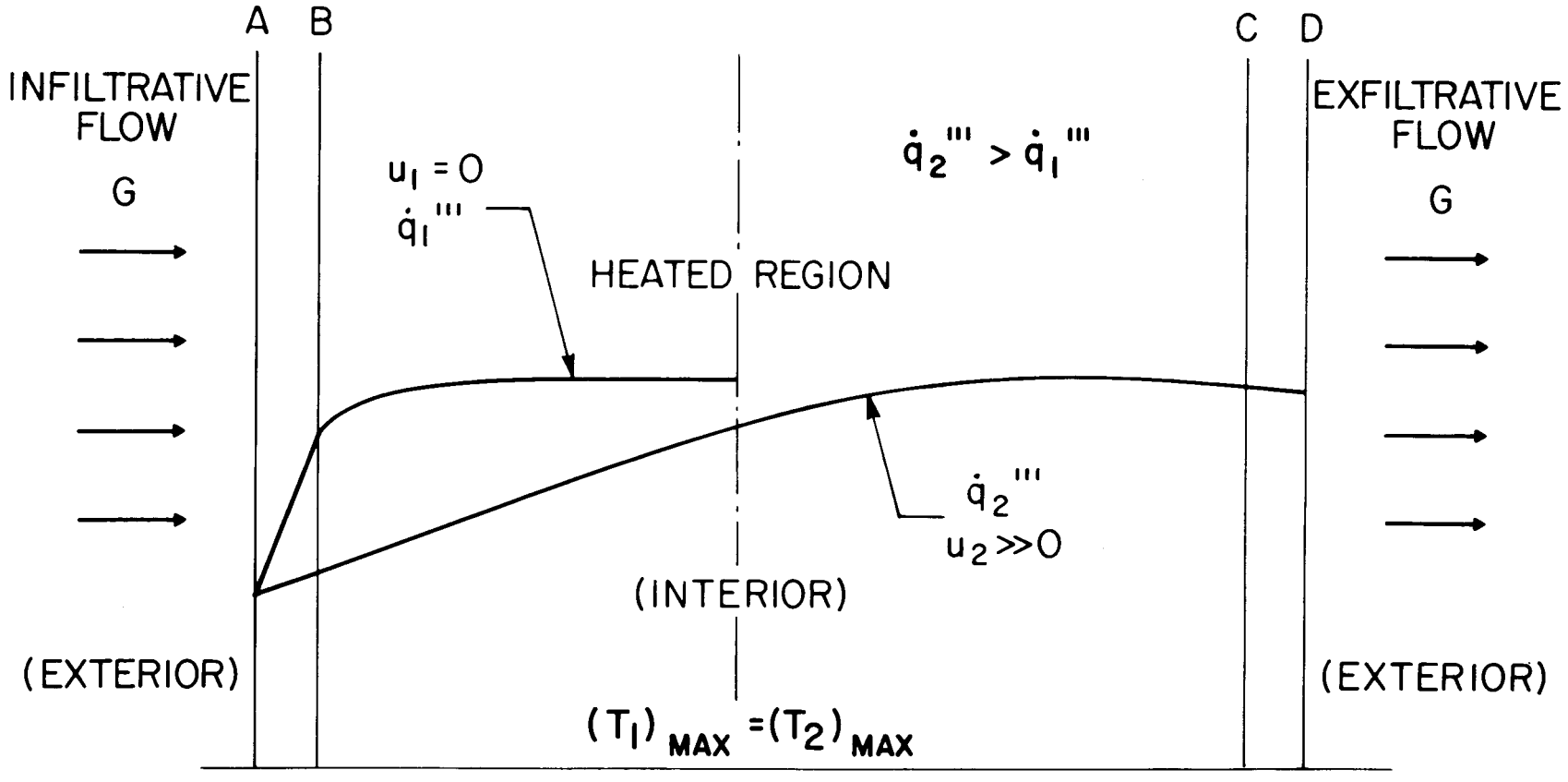


Fig. 11

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