Document D4:1972

Heat transfer in fibrous materials

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National Swedish Building Research

Värmetransport i fibrösa material

Claes G. Bankvall

Byggforskningen Sammanfattningar

D4:1972

Rapporten presenterar teorier för och mätningar av värmetransportmekanismerna i fibermaterial (dvs isolering av mineralullstyp). Arbetet är del av ett större forskningsprogram vid Institutionen för Byggnadsteknik I, LTH, som behandlar materialets funktion som värmeisolering. En preliminär version av rapporten publicerades på svenska 1970.

I det fibrösa materialet förekommer olika typer av värmetransport: värmeledning i fibrerna och gasen samt strålning. I rapporten beräknas dessa mekanismer teoretiskt. Teorierna verifieras experimentellt genom mätningar på ett glasfibermaterial i en speciellt konstruerad plattapparat. Det visas att teorierna ger en fullständig förklaring av värmetransportmekanismernas inverkan på materialets totala effektiva värmeledningsförmåga.

Inom byggnadssektorn har behovet av effektiva värmeisoleringsmaterial ökat pga ökade krav på komfort och krav på reducering av byggnadskostnaderna. Det är inte möjligt att bedöma ett isoleringsmaterials uppförande i en väggkonstruktion utan kännedom om hur olika typer av värme transporteras genom materialet. Ytterligare kunskaper om isoleringsmaterialets funktionssätt och egenskaper behövs för att materialet skall kunna utnyttjas effektivt.

Högisolerande material är t ex cellplaster och mineralull. Inom byggnadstekniken har särskilt de fibrösa materialen med öppet porsystem och relativt komplex värmetransportmekanism medfört svårigheter vid bedömning av byggnadskonstruktioner där sådant material utgör isolering.

Värmeledningsförmåga

I fibermaterialet förekommer olika typer av värmetransport: värmeledning i fast fas (fibrer), strålning i materialet och värmetransport i den i isoleringen inneslutna gasen. Den totala effektiva värmeledningsförmågan i ett fibermaterial, λ, kan uttryckas genom sambandet

$$\lambda = \lambda_G + \lambda_F + \lambda_R \tag{1}$$

där λ_G är den effektiva värmeledningsförmågan pga ledning i gas och beror på ledning i gasen och ledning i gas och fiber omväxlande. Den effektiva värmeledningsförmågan pga ledning i fast fas, λ_F, beror på direkt ledning i fibrer och kontaktpunkten mellan fibrer. Strålningens inverkan på värmeledningsförmågan betecknas λ_R.

Värmetransport pga fibrer och gas

Vid undersökning av värmeledningsförmågan pga fibrer och gas kan materialet behandlas som en kombination av fast fas och gasfas. Den effektiva värmeledningsförmågan kan då uttryckas som

$$\lambda_F + \lambda_G = \alpha(1-\epsilon_P)\lambda_S + \alpha\epsilon_P\lambda_g + (1-\alpha)\frac{\lambda_s\lambda_g}{\epsilon_S\lambda_s + (1-\epsilon_S)\lambda_g} \tag{2}$$

I denna ekvation anger α den del av materialet som antas orienterat parallellt med värmeflödesriktningen och $(1-\alpha)$ delen i serie. Detta illustreras i FIG. 1 på enhetsvolymen. Av figuren framgår det att förhållandet mellan porositets- (eller struktur-)parametrarna ϵ_S, ϵ_P, α kan uttryckas som

$$\epsilon = \alpha\epsilon_P + (1-\alpha)\epsilon_S$$

där ϵ är materialets totala porositet och λ_s anger den fasta fasens (fiberns) och λ_g gasens värmeldningsförmåga.

Gaskinetiska beräkningar visar att om gasens tryck i materialet reduceras så kan λ_G fortfarande beräknas ur ekvation (2) om gasens värmeledningsförmåga, i detta fall λ_{ge}, beräknas ur

$$\lambda_{ge} = \lambda_g \frac{pL_o}{pL_o + ET} \tag{3}$$

där p är trycket, T temperaturen och E en konstant som beror på gasen. L_O den "effektiva pordiamern" eller

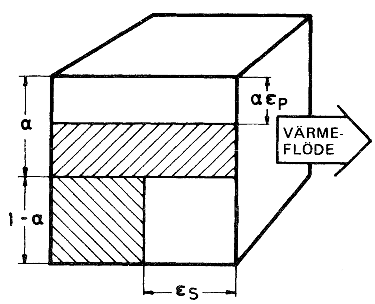

FIG. 1 Modell för beräkning av värmeledningen i gas och fibrer i ett fibröst material. Enhetsvolym.

Nyckelord:
värmetransportmekanism, värmeledningsförmåga, värmeisolering, fibermaterial, mineralull

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medelavståndet mellan fibrer anges av

$$L_o = \frac{\pi}{4} \cdot \frac{D}{1-\epsilon}$$

D är medelfiberdiametern.

Värmetransport pga strålning

Strålningen i ett fibermaterial av mineralullstyp är en mycket komplicerad process. Strålningen absorberas, transmitteras, reflekteras och sprids av fibrerna. Betrakta ett fibermaterial, som består av oordnade fibrer i skikt vinkelrät mot värmeflödesriktningen (jfr FIG. 2), om temperaturskillnaden är liten i förhållande till absoluttemperaturen kan den effektiva värmeledningsförmågan pga strålning fås ur

$$\lambda_R = \frac{4\sigma_s \cdot L_o \cdot T_m^3}{\left[\frac{1}{\beta} + \frac{L_o}{d}\left(\frac{2}{\Sigma_o} - 1\right)\right]} \qquad (4)$$

där T_m är materialets medeltemperatur, d dess tjocklek, Σ_o begränsningsytornas emittans och B en strålningsfaktor som beskriver strålningsegenskaperna hos fibrer och fiberskikt.

Resultat

En detaljerad undersökning av ett materials värmeisolerande egenskaper omfattar mätning av värmeisoleringsförmågan vid varierande temperatur såväl för oevakuerat som för evakuerat material samt bestämning av isoleringsförmågans förändring vid varierande gastryck. Avsikten med mätningarna är att bestämma materialets strålningsfaktor och strukturparametrar. Detta har gjorts för ett mineralullsmaterial av glasfiber i densiteter 15—80 kg/m³. Mätningarna utfördes i en ensidig, evakuerbar och roterbar plattapparat. FIG. 3—5 visar resultat från mätningar och teoretiska beräkningar.

FIG. 3 visar värmeledningsförmågan för ett oevakuerat material som funktion av temperaturen. De uppmätta punkterna ansluter väl till den beräknade kurvan.

Inverkan av reducerat gastryck på värmeledningsförmgan visas i FIG. 4. Bidraget från de olika värmetransportmekanismerna till den totala effektiva värmeledningsförmågan för materialet visas i FIG. 5. Denna inverkan kan sammanfattas enligt följande:

- ☐ Ledning pga gas lämnar det största bidraget till värmeledningsförmågan inom det studerade densitetsintervallet (15—80 kg/m³).
- ☐ Strålningen är av störst betydelse för material med låg densitet och leder i dessa fall till höga λ-värden.
- ☐ Ledning direkt i fast fas är betydelsefull för material med hög densitet och kan då leda till ökning av λ-värdet.
- ☐ Ökande medeltemperatur i materialet medför ökande värmeledningsförmåga, i synnerhet vid låga densiteter pga strålning.

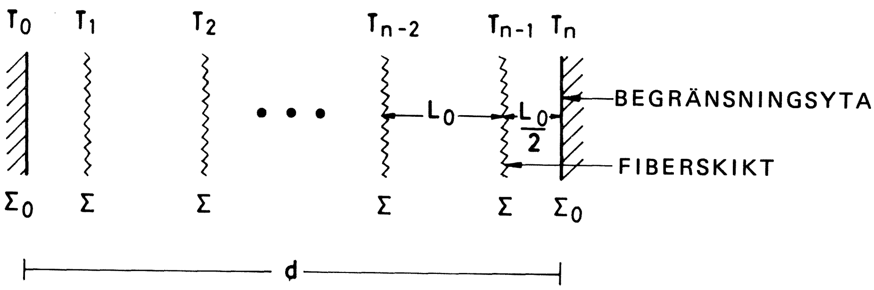

FIG. 2 Modell för beräkning av strålningen i ett fibermaterial.

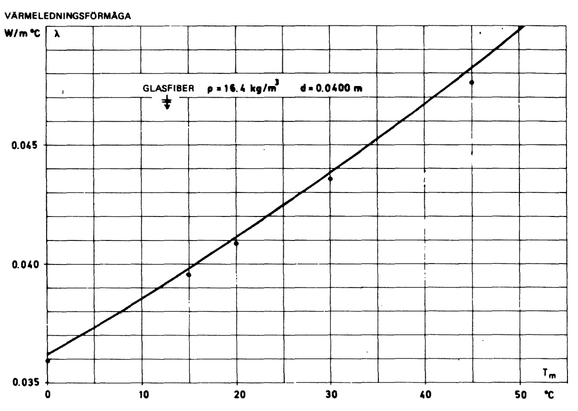

FIG. 3. Temperaturens inverkan på en fiberisolerings värmeledningsförmåga.

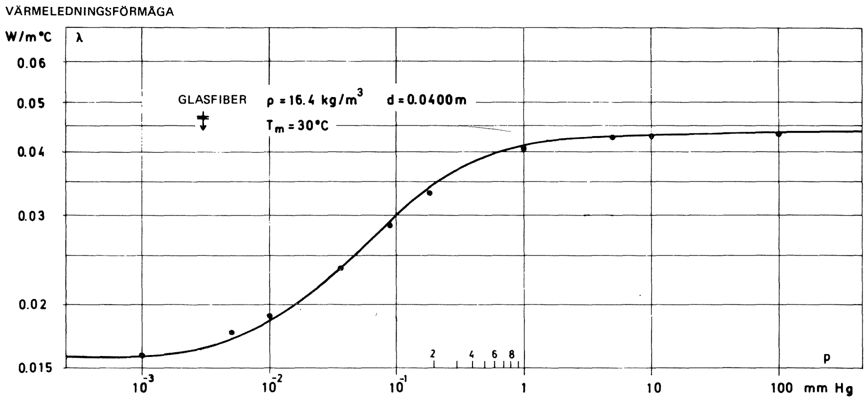

FIG. 4 Inverkan av reducerat lufttryck på ett fibermaterials värmeledningsförmåga.

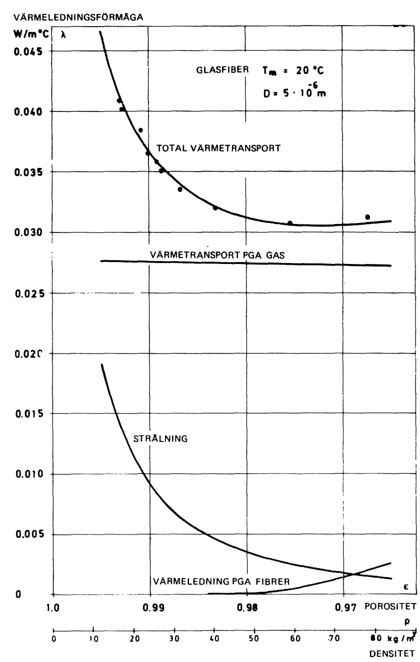

FIG. 5 Värmetransportmekanismerna i en fiberisolering.

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Heat transfer in fibrous materials

Claes G. Bankvall

National Swedish Building Research Summaries

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This report presents theories and measurements of the mechanisms of heat transfer in fibrous materials (e.g. insulation of mineral wool type), and measurements of these mechanisms. The present work is part of a larger research program at the Division of Building Technology, Lund Institute of Technology, for investigating the behaviour of fibrous material as thermal insulation. A preliminary version of this report was published in Swedish in 1970.

In the fibrous material different types of heat transfer are present: conduction in solid phase constituting the insulation, radiation in the material and heat transfer in the gas confined in the insulation. In the report the mechanisms of heat transfer are calculated theoretically. These calculations are verified experimentally by measurements on a glass fiber insulation in a specially constructed guarded hot plate apparatus. It is shown that the theories give a complete and consistent explanation of the influence of the mechanisms of heat transfer on the effective thermal conductivity of the fibrous material.

In the building sector the need for more effective heat insulators has increased, due to increasing requirements of comfort, and the necessity of reducing building costs. Further knowledge about the insulating effect and properties of the material in required in order to fulfil demands for a more effective utilization of the insulating material. It is not possible to judge the behaviour of an insulating material inside a wall construction without knowledge of the different types of heat transfer in the material itself.

Effective types of thermal insulation are, for example, materials of cellulare plastics and mineral wool. In building technology, especially, the fibrous insulation with open pore system and relatively complex mechanism of heat transfer has presented difficulties when evaluating building constructions where this material has been used for insulation.

Thermal conductivity

In the fibrous material different types of heat transfer are present: conduction in solid phase constituting the insulation, radiation in the material and heat transfer in the gas confined in the insulation. The total effective thermal conductivity of a fibrous material, λ, may be expressed as

$$\lambda = \lambda_G + \lambda_F + \lambda_R \tag{1}$$

where λ_G is the effective thermal conductivity due to conduction in gas and results from direct thermal conduction in the gas and conduction in gas and fibers alternatingly. The effective thermal conductivity due to conduction in solids, λ_F, results from direct conduction in fibers and fiber contacts. The influence of radiation on the effective thermal conductivity of the fibrous material is denoted by λ_R.

Heat transfer in fibers and gas

When investigating the thermal conduction in fibers and gas the fibrous material can be treated as a combination of a solid phase and a gas phase. The effective thermal conductivity in such a material can be expressed by

$$\lambda_F + \lambda_G = \alpha(1-\epsilon_P)\lambda_s + \alpha\epsilon_P \cdot \lambda_g + (1-\alpha)\cdot \frac{\lambda_s \cdot \lambda_g}{\epsilon_S \lambda_s + (1-\epsilon_S)\lambda_g} \tag{2}$$

In this equation α denotes the part of the material considered parallel to the heat flow and $(1-\alpha)$ the part in series with the heat flow. The situation can be illustrated by the unit volume of the material as in FIG. 1. From the figure it is obvious that the relation between the porosity (or structural parameters ϵ_S, ϵ_P and α can be written as

$$\epsilon = \alpha\epsilon_P + (1-\alpha)\epsilon_S$$

where ϵ is the total porosity of the material and λ_s is the thermal conductivity of the solid phase (fiber) and λ_g is the thermal conductivity of the gas.

Gas kinetical calculations show that if the pressure of the gas in the material is reduced, λ_G can still be calculated from equation (2) if the thermal conductivity of the gas in this case, λ_{ge}, is given by

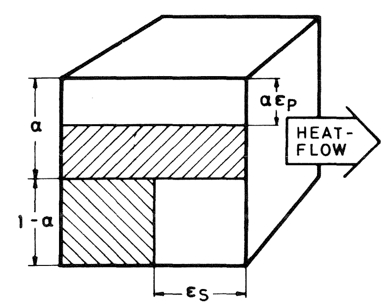

FIG. 1 Model for calculation of thermal conductivity due to gas and fibers in a fibrous material. Unit volume.

Key words:
mechanisms of heat transfer, thermal conductivity, thermal insulation, fibrous material, mineral wool

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$$\lambda_{ge} = \lambda_g \cdot \frac{pL_o}{pL_o + ET} \qquad (3)$$

where p is the pressure, T the temperature and E a constant depending upon the gas. L_O the "effective pore diameter" or the mean distance between fibers is calculated from

$$L_o = \frac{\pi}{4} \cdot \frac{D}{1-\epsilon}$$

D is the mean fiber diameter.

Heat transfer by radiation

The radiation in a fibrous material of mineral wool type is a very complicated process. The radiation will be absorbed, transmitted, reflected and scattered by the fibers. Consider a fibrous material consisting of disoriented fibers in layers at right angle to the heat flow (cf. FIG. 2), if the temperature difference is moderate in comparison to the absolute temperature, then the effective thermal concuctivity due to radiation can be calculated from

$$\lambda_R = \frac{4\sigma_s \cdot L_o \cdot T_m^{\,3}}{\left[\frac{1}{\beta} + \frac{L_o}{d}\left(\frac{2}{\Sigma_o} - 1\right)\right]} \qquad (4)$$

T_m is the mean temperature of the material, d its thickness, Σ_o the emissivity of the boundary surfaces and β a radiation coefficient describing the radiational properties of the fibers and fiber layers.

Results

A detailed investigation of the insulating properties of a fibrous material includes measurements of the thermal conductivity as a function of mean temperature of the unevacuated and the evacuated material and measurements of the dependance of the thermal conductivity upon the gas pressure. The object of the measurements is to establish the value of the radiation coefficient and the structural parameters. This has been done for a glass fiber mineral wool insulation in densities ranging from 15–80 kg/m³. The measurements were made in a one-sided, evacuable and rotatable guarded hot plate. FIG. 3–5 show results from measurements and theoretical calculations.

FIG. 3 shows the thermal conductivity of an unevacuated specimen as a function of temperature. The measured points agree well with the calculated curve.

The influence of reduced air pressure upon the thermal conductivity of a specimen is shown in FIG. 4.

The contribution of the different mechanisms of heat transfer to the total effective thermal conductivity is shown in FIG. 5. This influence can for the firbrous material be summarized as follows:

- ☐ Conduction due to gas contributes the largest part of the thermal conductivity in the range of density studied (15–80 kg/m³).
- ☐ Radiation is of greatest importance for low density materials and leads to high values of thermal conductivity in these cases.
- ☐ Conduction in solids is important in high density materials where it can lead to an increase in the thermal conductivity value.
- ☐ Increasing mean temperature of a material gives an increase in its thermal conductivity value. This is especially noticeable at low densities due to radiation.

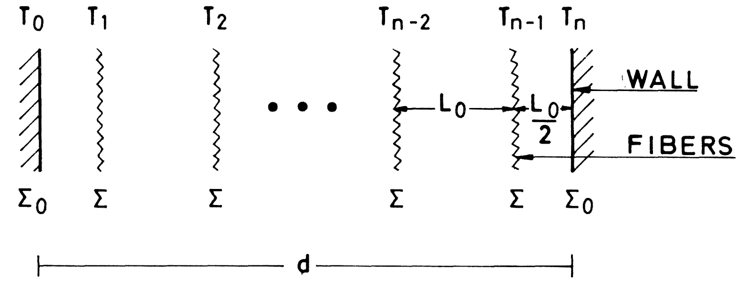

FIG. 2 Model for calculation of thermal conductivity due to radiation in a fibrous material.

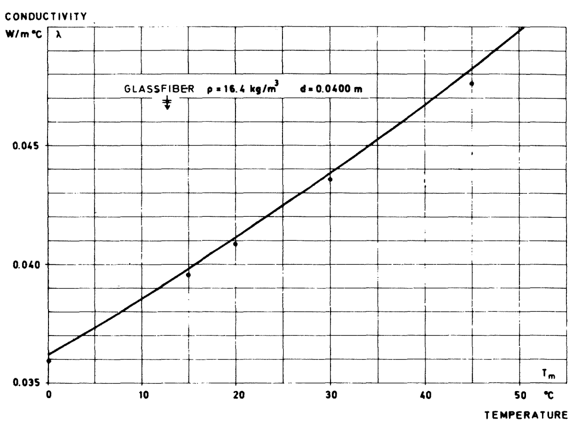

FIG. 3 The influence of temperature upon the thermal conductivity of a fiber insulation.

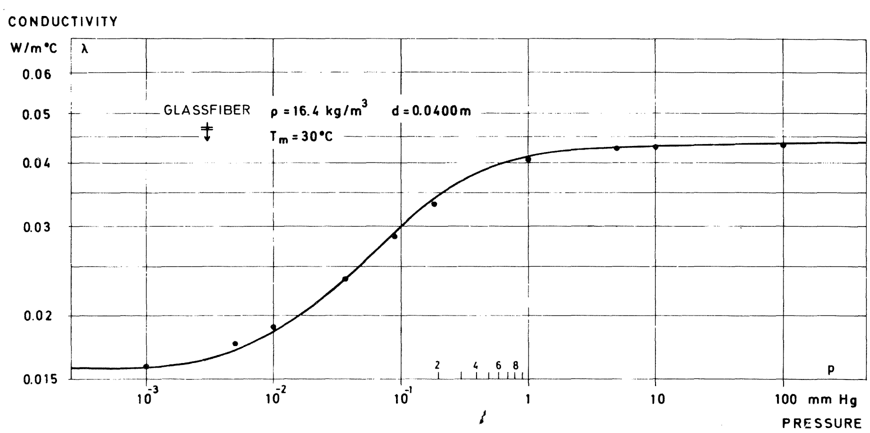

FIG. 4 The influence of reduced air pressure upon the thermal conductivity of a mineral wool material.

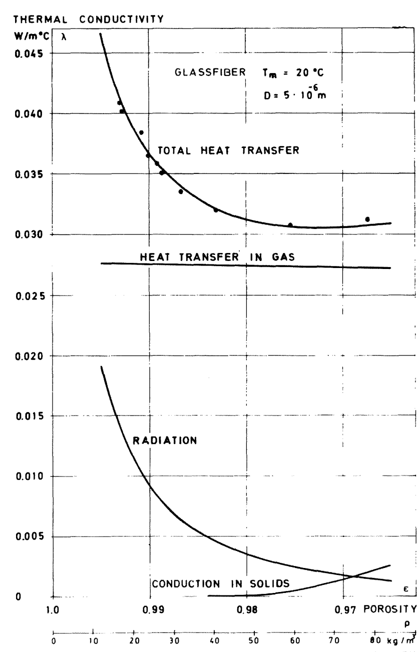

FIG. 5 The mechanisms of heat transfer in a fiber insulation.

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HEAT TRANSFER IN FIBROUS MATERIALS

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CONTENTS

FOREWORD

This report presents theories of the mechanisms of heat transfer in fibrous materials (e.g. insulation of mineral wool type), and measurements of these mechanisms.

The present work is part of a larger research program for investigating the behaviour of fibrous material as thermal insulation. It was then found necessary to investigate the different kinds of heat transfer, and their importance to the total thermal conductivity of the material. No decisive investigation of this nature has as yet been reported. The present investigation therefore deals with the physical mechanisms of heat transfer in fibrous materials. The experimental tests have been performed in a specially constructed guarded hot plate apparatus. The accuracy and versatility of this unit have been necessary for verification of the theories and for carrying out the research work.

A correct evaluation of the behaviour of an insulating material in a construction necessitates thorough knowledge of the heat transfer through the material. The present investigation consequently lays the foundation for measurements on an insulated construction which is the second part of the program. When also this part has been completed, it will be possible to correctly evaluate constructions insulated with fibrous materials.

I wish to thank those who have given their assistance to this project: Mr. Thord Lundgren, who helped with the measurements, Mrs. Lilian Johansson, who drew the figures for the report, and Mrs. Mary Lindqvist, who typed the manuscript. I am also indebted to my colleagues and friends who have shown interest in my work and given me helpful advice.

The first version of this report was published in Swedish in 1970 at the Lund Institute of Technology, Division of Building Technology.

Lund, October, 1971

Claes Bankvall

NOMENCLATURE

d	thickness of specimen	m
D	mean diameter of fiber	m
$\bar{L}$	mean free path of gas	m
L_o	mean distance between fibers	m
A	area	m^2
T	temperature	K (^oC)
T_o, T_n	temperature of boundary surfaces	K (^oC)
T_m	mean temperature	K (^oC)
ΔT	temperature difference	K (^oC)
Q	heat flow	W
q	heat flux	W/m^2
λ	(effective) thermal conductivity	W/mK (W/m^oC)
λ_e	effective thermal conductivity of evacuated material	W/mK (W/m^oC)
λ_g	thermal conductivity of gas	W/mK (W/m^oC)
λ_{ge}	thermal conductivity of gas at reduced pressure in material	W/mK (W/m^oC)
λ_s	thermal conductivity of solid phase	W/mK (W/m^oC)
λ_G	effective thermal conductivity due to conduction in gas	W/mK (W/m^oC)
λ_F	effective thermal conductivity due to conduction in solids	W/mK (Wm^oC)
λ_R	effective thermal conductivity due to radiation	W/mK (Wm^oC)
ρ	density	kg/m^3
ε	porosity	-
ε_P, ε_S, α	structural (porosity) parameters	-
Σ_o	emissivity of boundary surfaces	-
p	pressure	N/m^2 (mmHg)
σ_s	constant	$5.7 \cdot 10^{-8}$ W/m^2K^4
E	constant (cf. equation (2.11))	
β	radiation coefficient (cf. section 2.5)	

1 INTRODUCTION

Development and manufacture of new types of thermal insulation and their importance for technological development are especially pronounced in space technology, where the applications range from insulation of fuel tanks to parts of machinery, electronic equipment etc. Also in the field of building physics the need for more effective heat insulators has increased, due to increasing requirements of comfort, and the necessity of reducing building costs. Further knowledge about the insulating properties of the material is required in order to fulfil demands for a more effective utilization of the insulating material. This is especially true for many new types of highly insulating materials with complicated heat transfer mechanisms. It is not possible to judge the behaviour of an insulating material inside a wall construction without a knowledge of the different types of heat transfer in the material itself.

In the field of building physics and building technology effective types of thermal insulation are, for example, materials of cellular plastics and mineral wool. These materials as well as most other high performing insulators, are porous. The first material contains closed pores, and the second has open pores.

Mineral wool shows the most complicated type of heat transfer. Compared to a material with closed pores, the gas in the fibrous material is not enclosed in the pores. It is thus possible to experience a gas flow that influences the whole piece of material, and increases its effective thermal conductivity. In building physics, especially, this type of fiber insulation with open pore system and relatively complex mechanism of heat transfer has presented difficulties when evaluating building constructions where this material has been used for insulation. The influence of dimensional changes, temperature, temperature differences etc. have in many investigations not been conclusively evaluated, in certain cases due to faulty measuring techniques but mostly because adequate theories for the behaviour of the material from the point of heat transfer are lacking.

A correct evaluation of an insulating material and its behaviour in a construction presupposes - which should be stressed once again - thorough knowledge of the mechanisms of heat transfer in the material. In the present investigation a theory has been developed for the heat transfer in a fibrous material, that is in a porous material with open pore system. This theory is verified by measurements in a specially constructed guarded hot plate apparatus. This measuring equipment has been described in a previous report (Bankvall, 1970/72).

The intention of the present investigation has been to clarify the mechanisms of heat transfer in fibrous insulations. In most cases the behaviour of the material has been studied when the heat flow had a direction which would give no convective heat transfer, i.e. there was no flow of gas in the material. For materials with high porosity the influence of changing direction of heat flow has also been studied. The present investigation serves as a basis for measurements on wall constructions, in which case the theories as well as the measurements are expanded so as to include the influence of convective gas flow. A total picture of the heat transfer in a porous material with open pore system and of the evaluation of constructions where this material constitutes the thermal insulation can thereafter be given (Bankvall, 1971/72).

The theories and measurements are presented in the following order:

Chapter 2 gives the theoretical background for heat transfer in fibrous materials. The different types of heat transfer are mainly treated separately.

It is shown that the influence of gas upon thermal conductivity depends upon the structure of the material, which is indicated by two structural parameters. Both direct conduction in gas and conduction in fiber and alternatingly gas are considered.

The influence of gas pressure upon conduction in gas in the material is calculated by gas kinetic theory. For high porosity materials an expression is given for the mean distance between fibers.

The direct conduction in solids (fibers and fibercontacts) is calculated with the assumption of certain regularity and symmetry in the structure of the material. This calculation serves only to give the magnitude of this mechanism in the thermal conductivity of the material.

The complicated physics of radiation in a fibrous material especially in the mineral wool type in current use, is discussed and its dependence upon a radiational factor is calculated from a simple model of the material.

Chapter 2 is concluded by a summary of the total thermal conductivity of fibrous materials.

Chapter 3 gives a presentation of the different types of measurements that have been performed on a fibrous material to decide the influence of the different mechanisms of heat transfer.

Chapter 4 contains the main discussion of the different mechanisms of heat transfer and comparisons with measurements are presented. Comments are made upon the results and the relevance of the conceptions of thermal conductivity in fibrous materials which have been used so far. A summary is given of the total thermal conductivity in a fibrous material.

2 THEORETICAL MODEL FOR HEAT TRANSFER IN FIBROUS MATERIAL.

2.1 Introduction.

A thermal insulation consists either of a single material, a mixture of materials or a composite structure. The insulation is designed to reduce the heat flow between its surfaces at given temperatures. The effectivness of a thermal insulation is indicated by its thermal conductivity, which depends on the physical structure of the material. The thermal conductivity is defined as the property of a homogeneous body that is designated by the ratio of steady state heat flow per unit area to the temperature gradient in the direction perpendicular to the area. A material can be considered homogeneous when the thermal conductivity is independent on variations in area and thickness of the specimen over a small temperature range. In order to be meaningful, the thermal conductivity must be identified with respect to the mean temperature. For non-isotropic material, the thermal conductivity not only varies with temperature but also with orientation of heat flow.

Thermal conductivity is usually measured with the material exposed to a definite temperature difference. Because of the complex interactions of many different mechanisms of heat transfer, the term "effective" or "apparent" thermal conductivity is often used in order to distinguish this value from the ideal thermal conductivity value, which corresponds to a very small temperature difference. The behaviour of an insulating material generally depends upon temperature and emittance, of the boundary surfaces, its density, type and pressure of gas contained within it, its moisture content, etc.

Highly insulating materials are usually porous. This means that different types of heat transfer can be present; conduction in solid phase constituting the insulation, radiation in the material and heat transfer in the gas confined in the insulation. Since these types of heat transfer are present simultaneously and interact with each other, it is often difficult to separate the different types. It is thus suitable to use the concept effective thermal conductivity which is determined experimentally during steady state conditions and calculated from

$$Q = \lambda \cdot A \cdot \frac{\Delta T}{d} \qquad (2.1)$$

where

Q is the heat flow through the material

λ the equivalent thermal conductivity

A the area

ΔT the temperature difference over the material and

d its thickness

The object of developing more effective insulating materials is to reduce the influence of the different types of heat transfer, and for this purpose it is necessary to investigate the influence of the variable factors: conduction in solids, heat transfer in gas and radiation upon the heat transfer through the material.

The different mechanisms of heat transfer will partially be given separate treatment in the following sections. The theory is developed for a porous material with an open pore system and applications are made on mineral wool, that is fibrous materials. The treatment may, however, with certain simplifications, be applied to the investigation of porous materials with closed pore system.

2.2 Thermal conduction in fibers and gas.

Porous material may be treated as a combination of a solid phase and a gas phase. The intention in this section is to find mathematical relations for correlating the effective thermal conductivity of the two-phase combination with the thermal conductivities of the individual components. The simplest method for analytical purposes is to study the two extreme limits of the thermal conductivity of a two-phase mixture. FIG. 2.1 shows one of the extreme limits. Gas and solid phase are in this case in series in respect to the heat flow through the material. FIG. 2.2 shows the other extreme. The two phases are parallel in respect

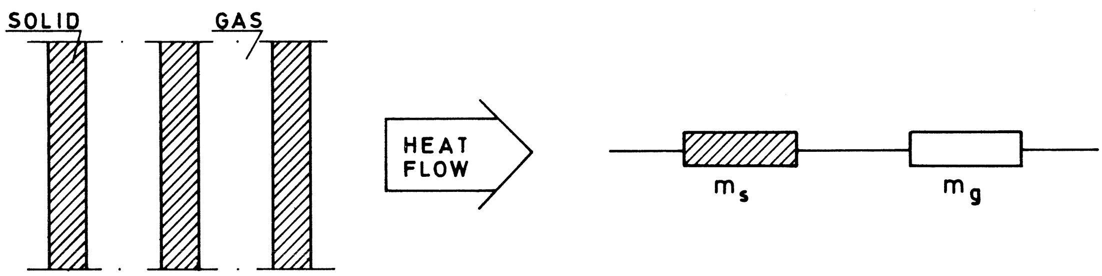

FIG. 2.1. Series case.

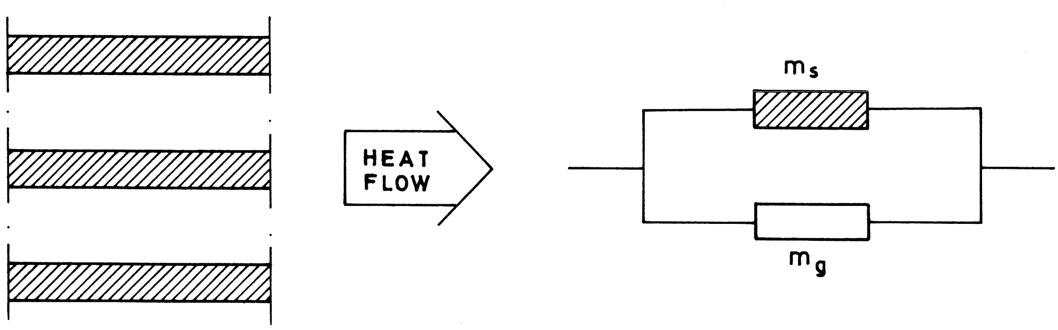

FIG. 2.2. Parallel case.

to the heat flow. The figures also illustrate the different limits by means of thermal resistances. The effective thermal conductivity in the series case (λ_S) is

$$\lambda_S = \frac{\lambda_g \lambda_s}{\lambda_g \cdot (1 - \varepsilon) + \lambda_s \cdot \varepsilon} \tag{2.2}$$

and in the parallel case (λ_P)

$$\lambda_P = \lambda_s \cdot (1 - \varepsilon) + \lambda_g \cdot \varepsilon \tag{2.3}$$

In these equations ε denotes the porosity of the material
λ_s the thermal conductivity of the solid phase and
λ_g the thermal conductivity of the gas.

In the figures, m_s and m_g denote the thermal resistance for solids and gas respectively. It is obvious that the true porous material has an effective conductivity somewhere between λ_S and λ_P. A closed pore material may be illustrated with thermal resistances as in FIG. 2.3.

Materials with open pores may be illustrated by a combination in parallel of the two extreme cases. This is shown in FIG. 2.4.

The effective thermal conductivity in such a material can be expressed by

$$\lambda = \alpha \cdot \left(\varepsilon_P \cdot \lambda_g + (1 - \varepsilon_P) \cdot \lambda_s\right) + (1 - \alpha) \frac{\lambda_s \lambda_g}{\varepsilon_S \cdot \lambda_s + (1 - \varepsilon_S) \cdot \lambda_g} \tag{2.4}$$

In this equation α denotes the part of the material considered parallel to the heat flow and $(1 - \alpha)$ the part in series with the heat flow. The situation can be illustrated by the unit volume of the material as in FIG. 2.5.

From the figure it is obvious that the relation between the porosity (or structural) parameters ε_S, ε_P and α can be written

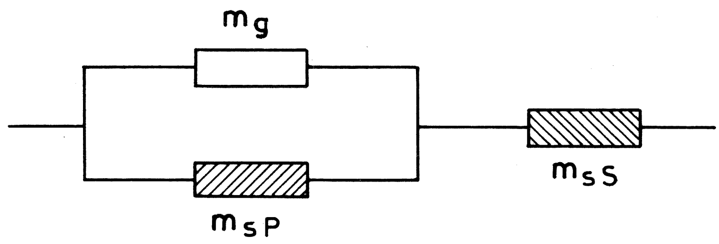

FIG. 2.3. Porous material with closed pore system.

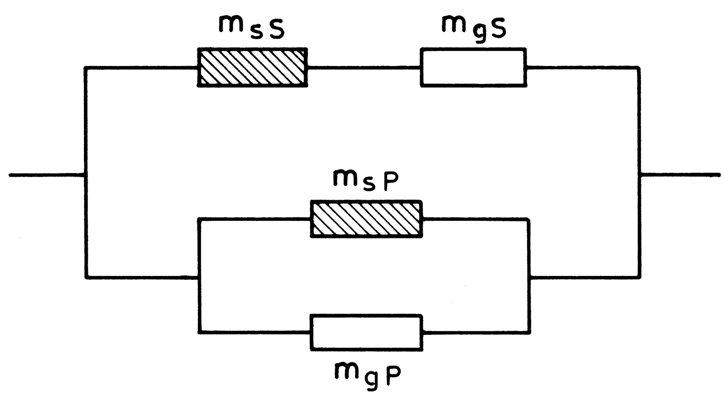

FIG. 2.4. Porous material with open pore system.

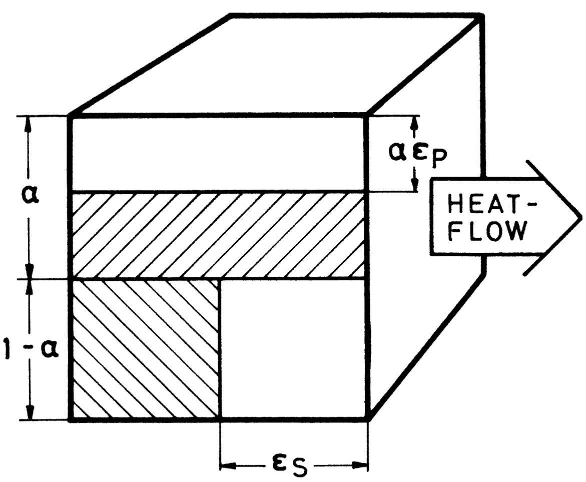

FIG. 2.5. Porous material with open pore system, unit volume.

$$\varepsilon = (1 - \alpha)\cdot\varepsilon_S + \alpha\cdot\varepsilon_P \qquad (2.5)$$

In this equation ε denotes the total porosity of the material.

The effective thermal conductivity in the fibrous material consequently depends upon two independent parameters (namely an arbitrary pairing of ε_S, ε_P and α).

FIG 2.5 shows that $\alpha\cdot(1 - \varepsilon_P)$ in equation (2.4) signifies the part of the thermal conductivity which is due to direct conduction in fibers and contacts between fibers. This part is generally small in high porosity materials. If the material is evacuated, it is this mechanism of heat transfer, together with the thermal radiation, that remains and governs the heat transfer through the material. In the following,

$$\lambda_F = \alpha\cdot(1 - \varepsilon_P)\lambda_s \qquad (2.6)$$

will be referred to as conduction in solids.

The remaining part of the thermal conductivity according to equation (2.4) is

$$\lambda_G = \alpha\cdot\varepsilon_P\cdot\lambda_g + (1 - \alpha)\cdot\frac{\lambda_s\,\lambda_g}{\varepsilon_S\cdot\lambda_s + (1 - \varepsilon_S)\cdot\lambda_g} \qquad (2.7)$$

λ_G is due to the gas in the material. The first part is the direct conduction in continuous gas channels of volume ratio $\alpha\,\varepsilon_P$, the other part, is due to interaction of fibers and gas, that is conduction in gas between fibers close to each other or conduction in the vicinity of point contacts between fibers.

λ_G denotes the influence of gas upon the effective thermal conductivity of the material and this is consequently the total change that can be expected when the material is evacuated. λ_G will in the following be referred to as conduction in (or due to) gas.

Depending upon the structure of the investigated material the treatment of the two phase system (equation (2.2) and (2.3) and the combinations of these) given above can be developed further to give more complex equations with fewer unknown parameters, or the equations can be simplified by neglecting some part of the conduction heat transfer.

Schuhmeister (1878) used a simplified and partly empirical version of equation (2.4) to calculate the thermal conductivity of wool. This formula was later used by Baxter (1946) to study the thermal conductivity of textiles. Verschoor and Greebler (1952) treat a glass fibrous insulation as though the volume fraction of fiber is in series with the volume fraction of gas, which means that the first part in equation (2.7) is omitted ($\alpha = 0$ and $\varepsilon_S = \varepsilon$). This approach has later been used by several researchers: Stephenson & Mark (1961), Arroyo (1967), Hager & Steere (1967), Mumaw (1968) and Tye & Pratt (1969). Pelanne (1968) and Andersen (1968) make the opposite assumption and neglect the second part of equation (2.7) ($\alpha = 1$ and $\varepsilon_P = \varepsilon$). Strong, Bundy & Bovenkerk (1960) simplified the influence of conduction in gas and used $\lambda_G = \lambda_g$.

The complete equation (2.4) was used by Willye & Southwick (1954) to study dirty sands. Krischer (1956) used the two extremes (equation (2.2) and (2.3)) to estimate the thermal conductivity of moist porous materials. In a theoretical evaluation of open-pore materials Calvet (1963) considered the two extremes and so did Lagarde (1965). In order to investigate the thermal conductivity of ceramics Flynn (1968) discussed the complete equation (2.4). In the study of fibrous insulations, however, the incomplete models described above have mostly been used.

A detailed theoretical calculation of the heat transfer through a porous material necessitates thorough knowledge - or extensive assumptions - about the structure of the material (cf. Kunii & Smith (1960), Luikov et. al. (1968) and Chang & Vachon (1970)). These calculations are often complicated and in many cases the structure of the material does not to any sufficient degree conform to that of the model of calculation. The calculated equations can therefore not always be verified experimentally.

Too crude simplifications at an early stage of the theoretical treatment may on the other hand lead to erroneous interpretations of the heat transfer in the material. This is not only the case when calculating the influence of conduction due to gas and fibers on the heat transfer, but also, as will be shown in later sections, when treating other types of heat transfer in the material. One´s object must be to find a model that is sufficiently detailed to adequately describe the behaviour of the material.

2.3 Thermal conductivity of gas.

In the preceding section the heat transfer in a fibrous material due to conduction in fibers and gas has been treated. In this section a more detailed treatment of the heat transfer in the gas will be made. For a free, ideal gas, the thermal conductivity can be written

$$\lambda_g = A \cdot C_v \cdot \eta \tag{2.8}$$

where

C_v is the specific heat of the gas at constant volume,

η is the dynamic viscosity and

A is a constant for a given gas.

The value of the constant depends upon whether the gas consists of one or more molecules, and what simplifications are made in the gas kinetical calculations (Tye & McLaughlin, 1969).

The viscosity may be expressed by

$$\eta = B \cdot \rho \cdot \bar{L} \cdot \bar{v} \tag{2.9}$$

where

B is a constant analog to A,

ρ is the density of the gas,

$\bar{L}$ the mean free path of the gas molecules and

$\bar{v}$ their mean velocity.

The mean free path of the molecules may be written

$$\bar{L} = \frac{M}{\sqrt{2} \cdot \rho \cdot N_a \cdot \delta^2\pi} \qquad (2.10)$$

In this equation

M is the molecular weight

N_a the Avogadro coefficient and

$\delta^2\pi$ the gas kinetical cross section of the molecule.

I.e.

$$\bar{L} = E \cdot T/p \qquad (2.11)$$

where p is the pressure and T the temperature of the gas. E is a constant for a certain gas. For air $E = 2.332 \cdot 10^5$ if p is measured in N/m^2, if p is given in mmHg then $E = 1.749 \cdot 10^{-7}$ (Chemical Rubber Co., 1970).

If the "effective pore diameter", that is the mean distance between fibers in the material, is large compared to the free mean path of the gas, then the gas in the material will behave as a free gas. If, on the other hand, the pore diameter is small compared to the free mean path, the number of collisions between gas molecules will be negligible compared to the number of collisions between gas molecule and fiber, that is the free mean path will be equivalent to the pore diameter.

According to kinetic gas theories, the likelihood that, the gas molecule will not collide with another during passage of the distance x is given by $e^{-x/\bar{L}}$. In the same way the likelihood that a gas molecule will not collide with a fiber during the distance x, and in the absence of other molecules, is given by e^{-x/L_o}, where L_o is the mean distance between the fibers. The likelihood that the gas molecule will not collide with another molecule or with a fiber is consequently given by

$$e^{-x\,(1/\bar{L}+1/L_o)}.$$

If an effective mean free path, L_e, for the gas molecule in the fibrous material is defined by

$$\frac{1}{L_e} = \frac{1}{\bar{L}} + \frac{1}{L_o} \tag{2.12}$$

then the likelihood for a molecule collision during the distance x is given by

$$\psi = 1 - e^{-x/L_e} \tag{2.13}$$

This means that when there is variation of pressure the thermal conductivity of the gas will be given by equation (2.8) and (2.9) if the free mean path is given by L_e in the equation (2.12).

Assuming that the collision between a gas molecule and fiber does not influence the velocity distribution of the molecules, which is in accord with Maxwell´s law of distribution, then the thermal conductivity of the gas is proportional to the mean free path, i.e.

$$\frac{\lambda_{ge}}{\lambda_g} = \frac{L_e}{\bar{L}} = \frac{L_o}{\bar{L} + L_o} \tag{2.14}$$

λ_g is the thermal conductivity of the free gas with the mean free path $\bar{L}$ and λ_{ge} is the thermal conductivity of the gas having the mean free path L_e in the material.

By inserting equation (2.11) in (2.14) the thermal conductivity of the gas in the material may be calculated

$$\lambda_{ge} = \lambda_g \cdot \frac{pL_o}{pL_o + E \cdot T} \tag{2.15}$$

In FIG. 3.2 the thermal conductivity λ_g for air is given for different temperatures.

When evaluating the effective pore diameter, that is the mean distance between fibers L_o, certain assumptions about the structure of the material have to be made.

In mineral wool with disoriented fibers arranged in layers at right angle to the temperature gradient it is relatively easy to evaluate L_o. Consider a unit area of the material with a thickness of x in the direction of the temperature gradient. The fiber volume will be $(1 - \varepsilon)\, x$ and the corresponding fiber length

$$(1 - \varepsilon) \cdot x \cdot \frac{4}{\pi \cdot D^2}$$

if the fibers are assumed cylindrical with the diameter D. The total projected fiber area in the direction x will thus be

$$(1 - \varepsilon) \cdot x \cdot \frac{4}{\pi \cdot D}$$

- under the assumption that the fibers only cross each other in a few places within the element x. This expression indicates the probability of a gas molecule colliding with a fiber when covering the distance x.

At very low pressures, when the collisions with fibers dominate the kinetic gas theory give the probability of gas fiber collision as

$$\psi = 1 - e^{-x/L_o} \tag{2.16}$$

By comparing with the earlier calculated probability and after developing the exponential function to the first order, L_o is given by

$$L_o = \frac{\pi}{4} \cdot \frac{D}{1 - \varepsilon} \tag{2.17}$$

This equation is illustrated in FIG. 2.6.

At reduced gas pressure the thermal conductivity of the gas λ_{ge} in the fibrous material is given by equation (2.15). The effective pore diameter L_o is given by equation (2.17).

When investigating powders, Kannuluik & Martin (1933) established experimentally the relationship

$$p/\lambda_{ge} = ap + b$$

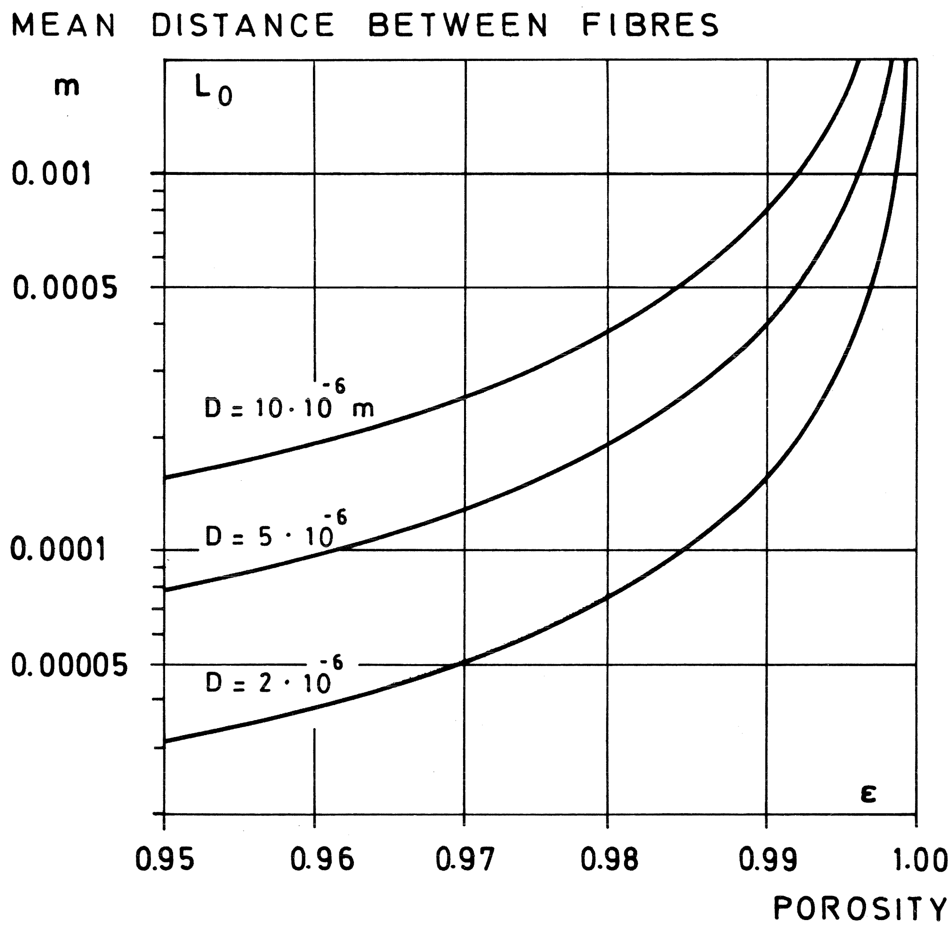

FIG. 2.6. Mean distance between fibers as a function of porosity.

with a and b constants. Allcut (1951) used this equation to study glass wool. It is evident that this is a simplification of equation (2.15) which is true if the temperature is kept constant in a certain gas. The gas kinetic considerations were used by Kistler (1935) and equation (2.15) was utilized to study the thermal conductivity of silica aerogel. Several researchers have since more or less used this relationship to investigate the influence of pressure on fibrous (or other open pore) materials (cf. Verschoor & Greebler, 1952; Strong, 1960; Calvet, 1963; Arroyo, 1967; Mumaw, 1968).

2.4 Thermal conduction in solid phase.

The solid phase in a fibrous material influences the heat transfer through the material in two ways. First by interaction between gas and fibers and second by direct heat conduction in fibers (i.e. heat transfer in the few fibers directly passing from the warm to the cold side of the specimen and the heat transfer through fibers and points of contact between them).

The fibers in mineral wool are normally oriented at random in parallel layers at right angle to the heat flow. It is obvious that a theoretical calculation of the thermal conductivity through fibers and fiber contacts can only be done if certain assumptions about the structure of the material are made. Since the intention is only to calculate the order of the thermal conductivity due to conduction in solids, λ_F, it will be assumed that the material consists of uniformly and symmetrically arranged fibers according to FIG. 2.7.

If D is the fiber diameter the number of fibers in each layer (of unit area) N, is

$$N = \frac{4(1 - \varepsilon)}{\pi \cdot D} \tag{2.18}$$

This means that the distance between fibers in the same layer is

$$L_o = \frac{\pi}{4} \frac{D}{(1 - \varepsilon)} \tag{2.19}$$

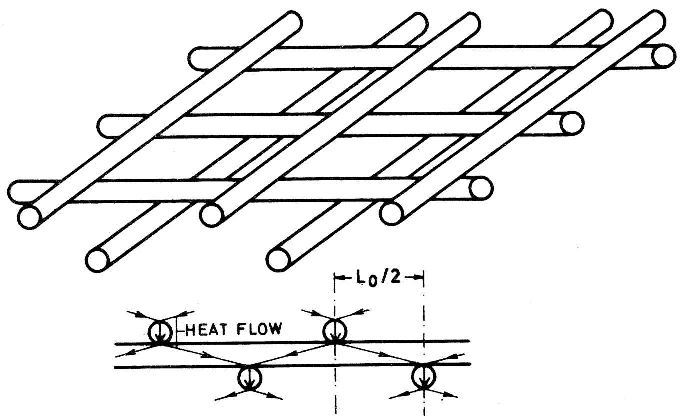

FIG. 2.7. Conduction in fibers and fiber contacts (solids).

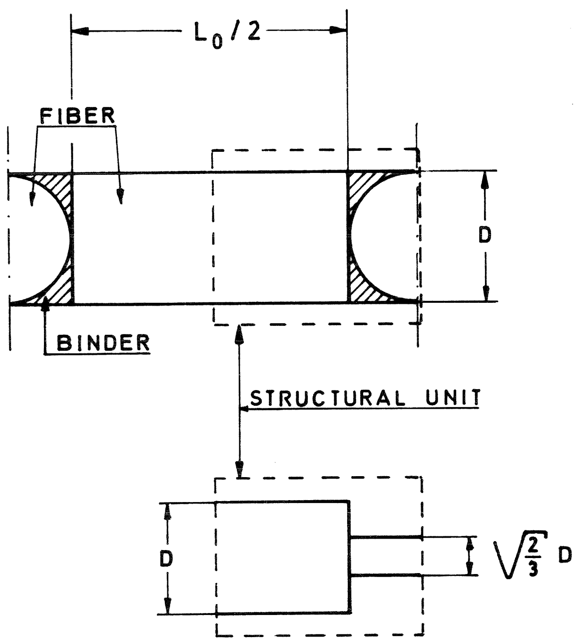

FIG. 2.8. Conduction due to solids.

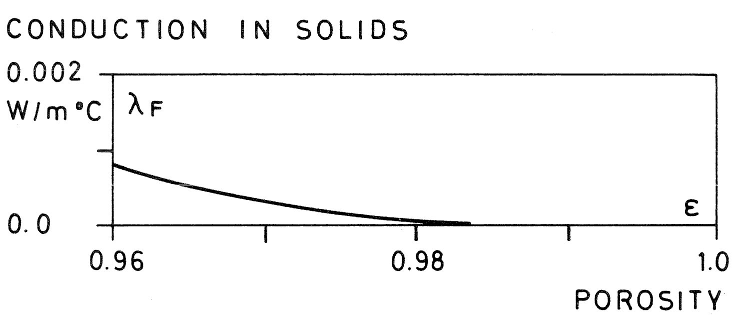

FIG. 2.9. Conduction due to solids (calculated from equation (2.23)).

This expression is the same as the earlier calculated mean distance between fibers (cf. equation (2.17)).

The heat transfer at a point of contact is due to direct contact between fibers and the binder surrounding the fibers. FIG. 2.8 is used in order to calculate the thermal conductivity through the point of contact. The upper part of the figure consists of a cylinder with plane ends connected to hemispheres and this figure is anticipated to be thermally equivalent to the marked area in FIG. 2.7. Since only a rough estimation of the thermal conductivity is needed, the lower figure (in FIG. 2.8) is used, where the hemisphere is replaced by a cylinder with the same volume as the hemisphere , and the influence of binder has been neglected (the thermal conductivity of the fiber usually being ten times that of the binder).

The thermal resistance of the marked structural unit in FIG. 2.8 is then

$$M = \frac{1}{\pi \cdot \lambda_s \cdot D} (3 + L_o/D) \tag{2.20}$$

The total heat flow per unit area through a fiber layer is given by

$$q = 2\,\frac{N^2}{M}\,\Delta T \tag{2.21}$$

ΔT denotes the temperature difference over a fiber layer.

The equivalent thermal conductivity of the material due to conduction in solids can now be calculated from

$$\lambda_F = 2\,\frac{N^2 D}{M} \tag{2.22}$$

or by use of equation (2.18) - (2.20)

$$\lambda_F = \frac{32(1-\varepsilon)^2 \cdot \lambda_s}{\pi\left(3 + \frac{\pi}{4(1-\varepsilon)}\right)} \tag{2.23}$$

As earlier ε is the porosity of the material and λ_s the thermal conductivity of the fiber.

Equation (2.23) is illustrated in FIG. 2.9. The figure shows that at high porosities the conduction in solids can be neglected when evaluating the total thermal conductivity of the material.

It is obvious from the above that it is not possible to make a detailed calculation of the conduction due to solids. Strong et. al. (1960) made an investigation of this factor in a glass fiber mat supporting a compressive mechanical load. Roughly the same model as above was used with the contact area between fibers being a function of contact pressure. This approach was also used by Arroyo (1967). A model where perfect contact was assumed between fibers arranged as in FIG. 2.7 was used by Hager & Steere (1967). All these models, however, predict the experimental results with the same degree of inefficiency and equation (2.23) will be used to estimate the thermal conductivity due to conduction in solids.

2.5 Thermal radiation in fibrous material.

The radiation in a fibrous material of mineral wool type is a very complicated process. It is difficult to calculate in detail the heat transfer due to radiation in such a material.

FIG. 2.10 shows the radiation from a black body as a function of wave length at a temperature of 25°C. The influence of temperature on the wave length of maximum radiation is given by Wien's displacement law. This is shown in FIG. 2.11 for the temperature region being considered. From the figures it is seen that the radiation has its maxima for wave lengths of about 10 μm (1 μm = $= 10^{-6}$ m).

The mean fiber diameter is about 5 μm for mineral wool of glass fiber. The fiber diameter is consequently of the same magnitude as the wave length of radiation at temperatures normal for building physics. This is the reason for the complicated mechanism of radiation in mineral wool. The radiation in this kind of

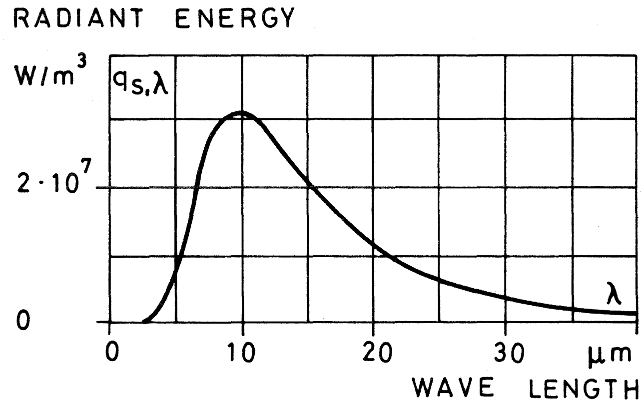

FIG. 2.10. Black body radiation at 25^{o}C as a function of wave length.

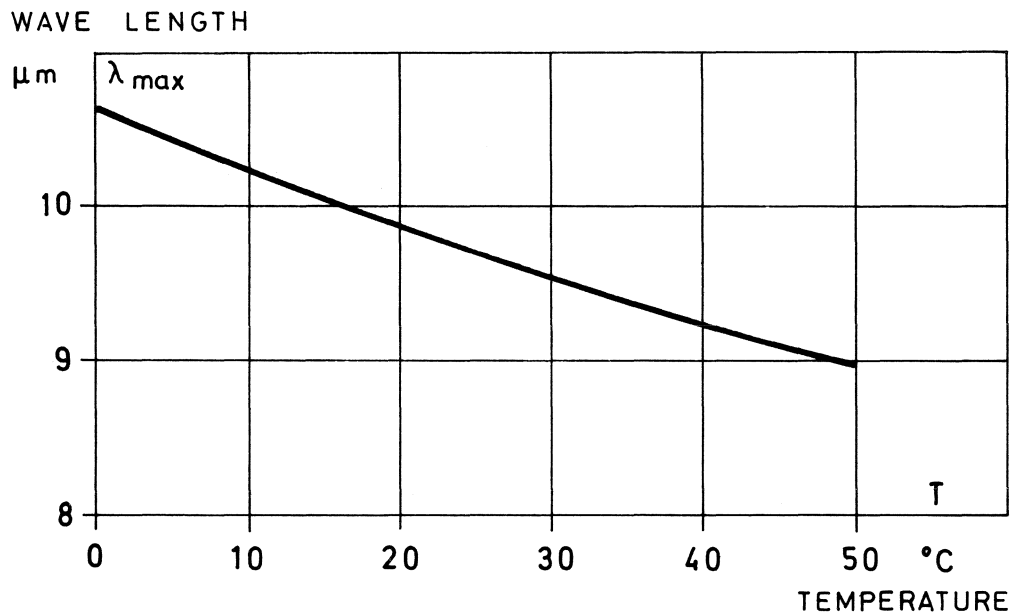

FIG. 2.11. The influence of temperature on the wave length of maximal radiation.

fibrous material will be absorbed, transmitted, reflected and scattered by the fibers. Thus it is very difficult to give a physically complete and correct picture of the radiation. In general simplified equations are used making certain assumptions about the behaviour of the fibers and the structure of the material.

Consider a fibrous material consisting of disoriented fibers in layers at right angle to the heat flow according to FIG. 2.12. In the figure, d is the thickness of the material, L_o the distance between fiber layers and T_o and T_n the wall temperatures. It is also assumed that the walls and the fiber layers behave as grey, non-transparent bodies with emissivity Σ_o and Σ respectively. Under these conditions the heat flow through the unit area is

$$q = \frac{\sigma_s(T_o^4 - T_1^4)}{\frac{1}{\Sigma_o} + \frac{1}{\Sigma} - 1} = \frac{\sigma_s(T_1^4 - T_2^4)}{\frac{2}{\Sigma} - 1} = \ldots =$$

$$= \frac{\sigma_s(T_{n-2}^4 - T_{n-1}^4)}{\frac{2}{\Sigma} - 1} = \frac{\sigma_s(T_{n-1}^4 - T_n^4)}{\frac{1}{\Sigma_o} + \frac{1}{\Sigma} - 1} \tag{2.24}$$

$$\sigma_s = 5.7 \cdot 10^{-8} \text{ W/m}^2 \text{ K}^4$$

Addition of the first and the last expression in (2.24) gives

$$2q = \frac{\sigma_s}{\frac{1}{\Sigma_o} + \frac{1}{\Sigma} - 1} (T_o^4 - T_1^4 + T_{n-1}^4 - T_n^4)$$

and the addition of the rest gives

$$(n - 2) \cdot q = \frac{\sigma_s}{\frac{2}{\Sigma} - 1} \sum_1^{n-2} (T_i^4 - T_{i+1}^4) = \frac{\sigma_s}{\frac{2}{\Sigma} - 1} (T_1^4 - T_{n-1}^4)$$

Elimination of $T_1^4 - T_{n-1}^4$ in the above gives

$$q = \frac{\sigma_s(T_o^4 - T_n^4)}{(n - 1)\left(\frac{2}{\Sigma} - 1 + \frac{1}{n - 1}\left(\frac{2}{\Sigma_o} - 1\right)\right)} \tag{2.25}$$

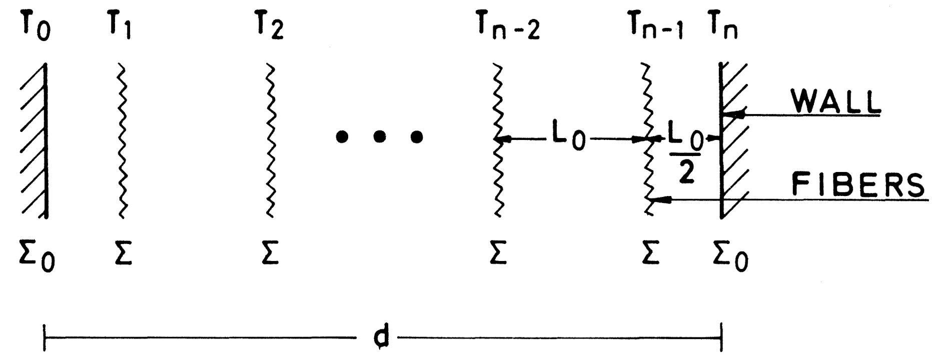

FIG. 2.12. Model for radiation in a fibrous material.

If the temperature difference is moderate in comparison to the absolute temperature, and if $n - 1 = d/L_o$ is inserted, then the effective thermal conductivity due to radiation λ_R can be calculated from

$$\lambda_R = \frac{4\sigma_s \cdot L_o \cdot T_m^{\;3}}{\left(\frac{1}{\beta} + \frac{L_o}{d}\cdot\left(\frac{2}{\Sigma_o} - 1\right)\right)} \tag{2.26}$$

where T_m is the mean temperature of the material and

$$\beta = \frac{\Sigma}{2 - \Sigma} = f(T, D, \varepsilon) \tag{2.27}$$

The simplifications made above infer that the factor β, describing the radiational properties of the fibers and fiber layers, is dependent upon temperature, mean fiber diameter and porosity.

From equation (2.26) it can be seen that the thickness of the material d, the mean fiber distance L_o and the emittance Σ_o of the boundary surfaces will influence the conductivity due to radiation. If, however, the thickness of the material is large in comparison to L_o and the boundary surfaces sufficiently black then the effective thermal conductivity due to radiation is given by

$$\lambda_R = 4\,\sigma_S \cdot L_o \cdot \beta \cdot T_m^{\;3} \tag{2.28}$$

L_o can be interpreted as the mean free path for photons and will then be given by equation (2.17)

$$L_o = \frac{\pi}{4}\,\frac{D}{1 - \varepsilon} \tag{2.29}$$

Verschoor & Greebler (1952) developed an expression similar to equation (2.28) when investigating glass fibrous insulation and called $\beta = 1/\alpha^2$ the opacity factor, α being the fraction of incident radiation energy absorbed by a fiber plane. This approach was also used by Mumaw (1968). Strong et. al. (1960) studied the radiation absorbed by a fiber and integrated over a spherical element, which also resulted in an equation similar to (2.28).

Radiation transfer through a porous insulation by direct transmission, scattering, absorption and reradiation was treated by Larkin & Churchill (1959). Taking into consideration the influence of the boundary surfaces, their calculations led to equations essentially the same as (2.26) with two parameters describing the radiational properties of the material. Poltz (1962) and Koglin (1967) with similar approaches, also arrived at equation (2.26). The influence of the boundary surfaces is treated by Hager & Steere (1967) and Pelanne (1968) in a simplified manner omitting some of the influencing factors. The influence of boundary surfaces on the thermal conductivity of cellular plastics was investigated experimentally by Fischer (1966) and by Fritz & Küster (1970).

It is possible to make a more or less complete treatment of the radiation in a material (cf. Holman, 1967 and Love, 1968). In the fibrous insulation, however, the effective thermal conductivity due to radiation, λ_R, is described by equation (2.26) and (2.28).

2.6 The total heat transfer in a fibrous material.

The total effective thermal conductivity of a fibrous material can be evaluated from the preceding sections. It is then found that the thermal conductivity may be expressed

$$\lambda = \lambda_G + \lambda_F + \lambda_R \qquad (2.30)$$

λ_G is the thermal conductivity due to conduction in gas and results from direct thermal conduction in the gas and conduction in gas and fibers alternatingly

$$\lambda_G = \alpha \cdot \varepsilon_P \cdot \lambda_g + (1 - \alpha) \cdot \frac{\lambda_s \lambda_g}{\varepsilon_S \cdot \lambda_s + (1 - \varepsilon_S) \cdot \lambda_g} \qquad (2.31)$$

λ_g and λ_s denotes the thermal conductivity of the gas and the solid phase respectively. The structural parameters ε_S, ε_P and α depends upon the porosity ε according to

$$\varepsilon = (1 - \alpha) \cdot \varepsilon_S + \alpha \cdot \varepsilon_P \qquad (2.32)$$

The meaning of the parameters is explained in FIG. 2.5.

If the gas pressure in the material is reduced, λ_G can still be calculated from equation (2.31) if the thermal conductivity of the gas in this case, λ_{ge}, is given by

$$\lambda_{ge} = \lambda_g \cdot \frac{pL_o}{pL_o + E\,T} \tag{2.33}$$

p is the pressure, T the temperature and E a constant depending upon the gas. L_o the "effective pore diameter" or the mean distance between fibers can be calculated from

$$L_o = \frac{\pi}{4}\frac{D}{1 - \varepsilon} \tag{2.34}$$

where D is the mean diameter of the fibers.

The effective thermal conductivity due to conduction in solids λ_F is given by

$$\lambda_F = \alpha(1 - \varepsilon_P)\cdot\lambda_s \cong \frac{32\cdot(1 - \varepsilon)^2\cdot\lambda_s}{\pi(3 + \frac{\pi}{4(1 - \varepsilon)})} \tag{2.35}$$

λ_F results from direct conduction in fibers and fibercontacts. The first relation above can only be used when all the structural parameters are known. The second relation is simpler to use when calculating λ_F, the result, however, is very approximate and will only be used for a preliminary estimation.

The influence of radiation on the effective thermal conductivity of the fibrous material is denoted by λ_R.

$$\lambda_R = \frac{4\cdot\sigma_s\cdot L_o\cdot T_m^3}{(\frac{1}{\beta} + \frac{L_o}{d}(\frac{2}{\Sigma_o} - 1))} \tag{2.36}$$

T_m is the mean temperature of the material and d its thickness. Σ_o is the emissivity of the boundary surfaces. β is a coefficient describing the radiational properties of the material.

$$\beta = f(T,\ D,\ \varepsilon) \tag{2.37}$$

When a material is evacuated, the remaining effective thermal conductivity is $\lambda_F + \lambda_R$, and λ_G is, consequently, the maximal decrease in thermal conductivity that can be expected.

The total effective thermal conductivity in a fibrous material can be written

$$\lambda = \alpha \cdot \varepsilon_P \cdot \lambda_g + (1 - \alpha) \cdot \frac{\lambda_s \lambda_g}{\varepsilon_S \cdot \lambda_s - (1 - \varepsilon_S) \cdot \lambda_g} + \alpha(1 - \varepsilon_P) \cdot \lambda_s + $$

$$+ \frac{4 \cdot \sigma_s \cdot L_o \cdot T_m^3}{\left\{\frac{1}{\beta} + \frac{L_o}{d}\left(\frac{2}{\Sigma_o} - 1\right)\right\}} \tag{2.38}$$

3 MEASUREMENTS OF THE MECHANISMS OF HEAT TRANSFER IN A FIBROUS MATERIAL.

3.1 Introduction.

The investigation of the different mechanisms of heat transfer in a fibrous insulation is described in the following sections. The intention was to establish the unknown **parameters** in the previously developed theoretical model. A detailed discussion of results and comparisons between calculated and measured values of the effective thermal conductivities will be given in Chapter 4.

3.2 Material.

The fibrous material investigated was glass fiber mineral wool. It was studied in densities ranging from 15–80 kg/m^3. The amount of binder in the material was about 5 % of the weight. From the chemical composition of the glass, the density of the solid phase was calculated to 2400 kg/m^3 and its thermal conductivity, λ_s, to 1.1 W/m^oC. The mean fiber diameter, D, was $5 \cdot 10^{-6}$ m (5 μm) (cf. Bankvall, 1969).

The relation between the (total) density of a material, ρ, and its porosity, ε, is given by

$$\varepsilon = 1 - \frac{\rho}{\rho_s} \tag{3.1}$$

ρ_s is the density of the solid phase. FIG. 3.1 illustrates equation (3.1).

Values for the thermal conductivity of the gas can be found in the literature (NBS, 1955). For air, the variation of λ_g with temperature is given in FIG. 3.2.

3.3 Experimental procedure and measuring equipment.

A detailed investigation of the insulating properties of a porous material includes three types of measurements. One series

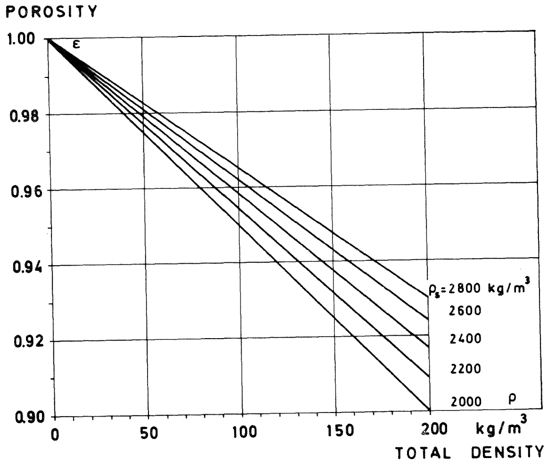

FIG. 3.1. Porosity as a function of total density and density of solid phase.

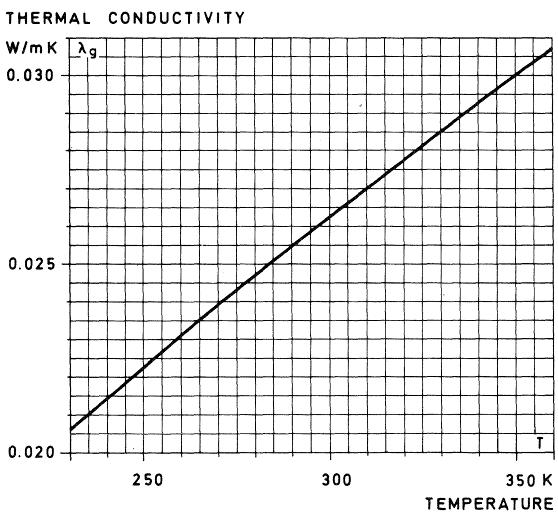

FIG. 3.2. Thermal conductivity of air as a function of temperature (NBS, 1955).

of measurements is made in order to investigate the thermal conductivity as a function of the mean temperature of the unevacuated material, and one to investigate the evacuated material. Thirdly, the dependence of the thermal conductivity upon the gas pressure is investigated. In the measurements the temperature difference over the material is chosen so as to give reliable results. This depends, among other things, upon the measuring equipment. If convective gas flow is not present, and the radiation in the material is moderate the temperature difference is of little importance for the effective thermal conductivity. In those cases where convection may be present, or radiation predominant, it is suitable to study the influence of the temperature difference on the thermal conductivity.

The object of the measurements is to establish the radiation coefficient β and the structural parameters ε_S, ε_P and α (of which only two are unknown since the third can be calculated from the known total porosity ε of the material).

The equipment that has been used was described in detail in a previous report (Bankvall, 1970/72), because of this only the more important characteristics will be noted here.

The measurements were done in a one-sided, evacuable and rotatable guarded hot plate apparatus. In this unit, the temperature on the hot plate can be varied between $+25^{\circ}C$ and $+85^{\circ}C$ and on the cold between $-30^{\circ}C$ and $+40^{\circ}C$. The gas pressure can be varied between about 760 mmHg and $< 10^{-3}$ mmHg. The influence of edge heat losses is very small and allows tests to be performed with sufficient accuracy on materials up to 7 cm in thickness. The temperature regulation is highly accurate and stable, with a resolution of $0.01^{\circ}C$ in the setting of the plate temperatures. Automatic regulation gives the equipment great rapidity. The measuring accuracy is better than 1 %. The lay out of the guarded hot plate is shown in FIG. 3.3.

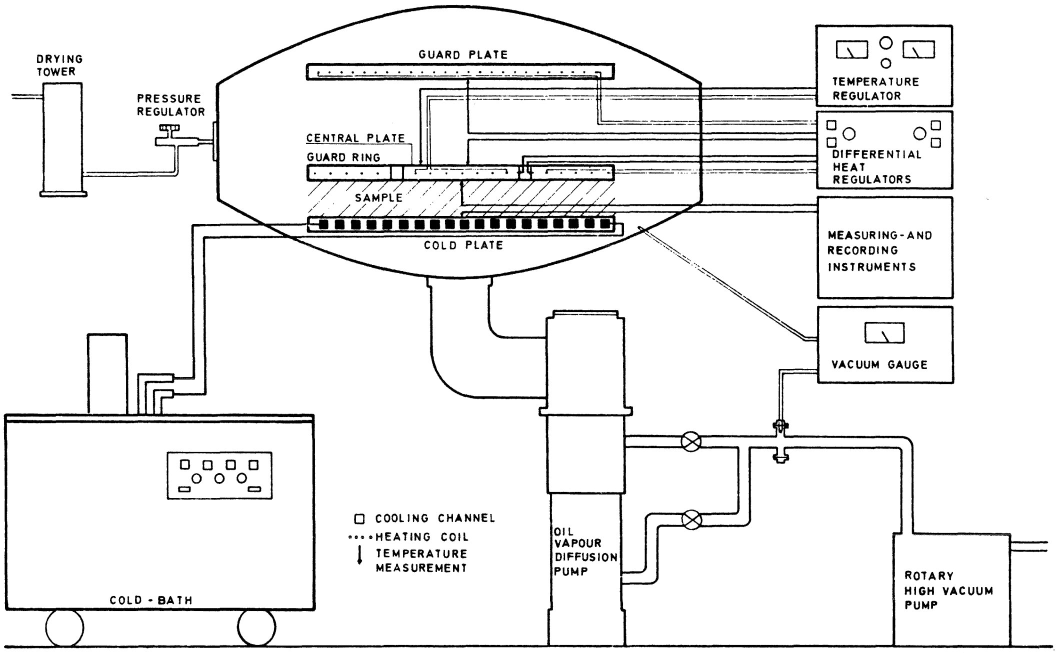

FIG 3.3. Layout of the guarded hot plate apparatus.

3.4 Conduction in solids and radiation. The radiation coefficient.

When evacuating a fibrous material the effective thermal conductivity of the material is given by

$$\lambda_e = \lambda_F + \lambda_R$$

with

$$\lambda_F = \frac{32(1-\varepsilon)^2 \cdot \lambda_s}{\pi(3 + \frac{\pi}{4(1-\varepsilon)})} \qquad (= \alpha(1-\varepsilon_P)\cdot\lambda_s) \qquad (3.2 = 2.35)$$

and

$$\lambda_R = 4\cdot\sigma_s\cdot L_o\cdot T_m^3\cdot\beta \qquad (3.3 = 2.36)$$

$$L_o = \frac{\pi}{4}\frac{D}{1-\varepsilon} \qquad (3.4 = 2.34)$$

$$\beta = f(T, D, \varepsilon) \qquad (3.5 = 2.37)$$

if the influence of the boundary surfaces on radiation is neglected.

The table in FIG. 3.4 summarizes some measurements on the evacuated glass fiber material. These values were used to find β in the following way:

λ_F was directly calculated from equation (3.2). The results are shown in FIG. 3.4. Since $\lambda_R = \lambda_e - \lambda_F$ it is now possible from the measured λ_e-values to calculate β. This was done at 20°C for different porosities and the result is shown in FIG. 3.5.

The figure shows that at high porosities these points describe a straight line. At low porosities, however, the β-value increases markedly when porosity decreases. This means that the radiation through the material should increase with decreasing porosity. This is physically inconsistent. Furthermore, for those materials where the β-value does not conform to a

ρ kg/m^3	ε	L_s m	λ W/m$^\circ$C 0°C	20°C (measured)	50°C	λ_F W/m$^\circ$C (from equation (3.2))	(from measurements)
16.4	0.9932	0.0005775	0.0108	0.0142	0.0204		
17.7	0.9926	-	-	0.0130	-		
21.8	0.9909	-	-	0.0112	-		
22.7	0.9905	-	-	0.0097	-		
23,5	0.9902	0.0004007	-	0.0095	-		
28,5	0.9881	-	-	0.0079	-		
31,4	0.9869	0.0002998	0.0050	0.0067	0.0098		
40,2	0.9832	0.0002338	-	0.0047	-	(0)	0.0001
59,3	0.9753	0.0001590	-	0.0033	-	(0.0002)	0.0006
78,6	0.9672	0.0001197	0.0027	0.0036	0.0052	(0.0004)	0.0020

FIG. 3.4. Measured thermal conductivity of evacuated glass fiber material.

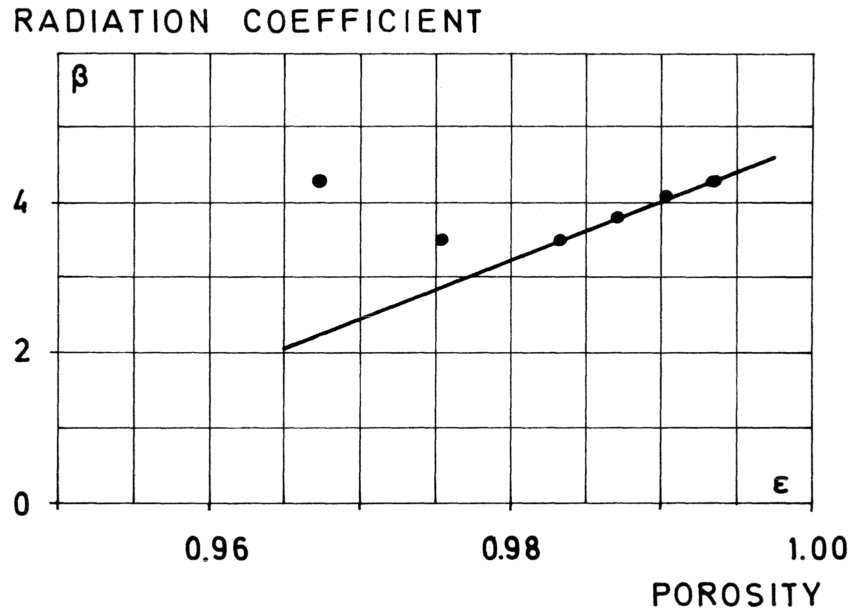

FIG. 3.5. Radiation coefficient β at 20°C.

● measured values

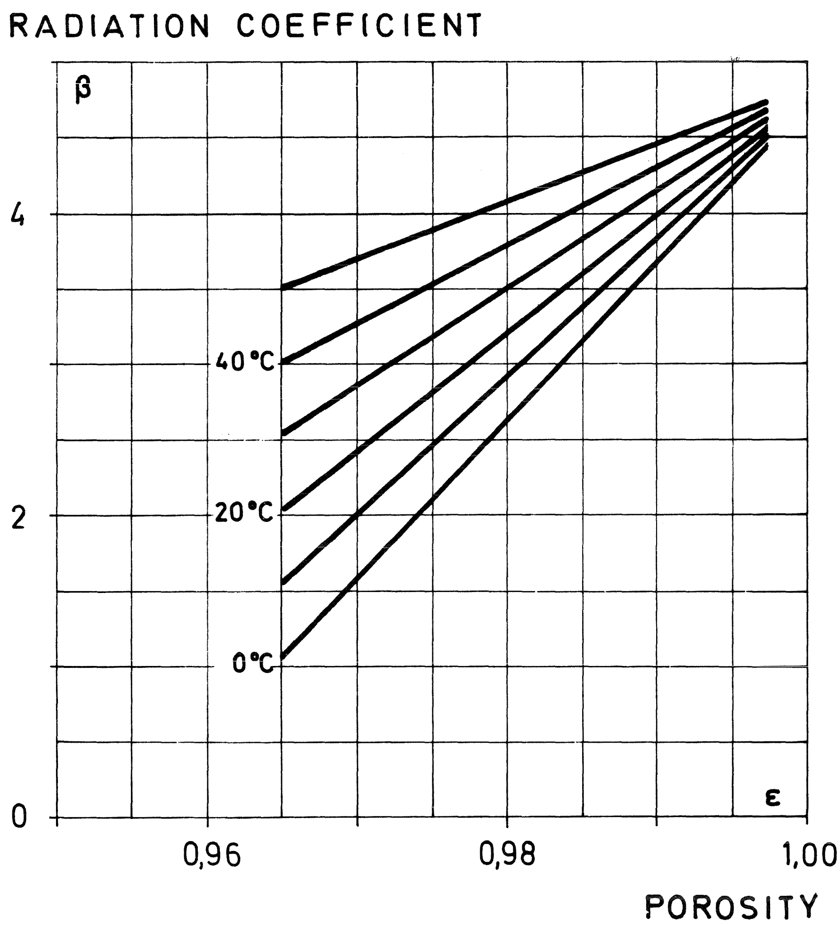

FIG. 3.6. Radiation coefficient β as a function of porosity and temperature.

straight line, the conduction in solid, λ_F, has been calculated from equation (3.2) and is consequently strongly dependent upon the accuracy of this equation. If all the points conformed to the straight line in FIG. 3.5, then the λ_F-values would be equal to those given last in the table in FIG. 3.4. This change of the value for the contribution of conduction in solids to the thermal conductivity of the material is well within the degree of accuracy of the earlier evaluations (cf. section 2.4).

The radiation coefficient β should decrease to zero at low porosities. The curve describing β will consequently have its steepest part at high porosities. The straight line thus gives an adequate description of the influence of porosity (in the studied range) upon the radiation coefficient β. What will be accepted as true λ_F values has been found and it is possible to calculate the radiation coefficient for other temperatures than 20°C. The result of this is shown in FIG. 3.6.

In this way the true thermal conductivity due to conduction in solids has been established (given in the last column in FIG. 3.4) as a function of porosity. The influence of temperature and porosity upon the radiation coefficient β have also been found (FIG. 3.6).

3.5 Conduction in gas. The structural parameters.

The contribution from conduction in gas to the effective thermal conductivity in a fibrous material is given by

$$\lambda_G = \alpha \cdot \varepsilon_P \cdot \lambda_g + (1 - \alpha) \cdot \frac{\lambda_s \cdot \lambda_g}{\varepsilon_S \cdot \lambda_s + (1 - \varepsilon_S) \cdot \lambda_g} \qquad (3.6 = 2.31)$$

and

$$\varepsilon = (1 - \alpha) \cdot \varepsilon_S + \alpha \cdot \varepsilon_P \qquad (3.7 = 2.32)$$

The table in FIG. 3.7 summarizes some measurements on unevacuated and evacuated material..The table also includes the λ_F-value calculated in the preceding section.

ρ kg/m^3	ε	λ W/m^{o}C (20^{o}C measured)	λ_e W/m^{o}C	λ_F W/m^{o}C	α	ε_S	ε_P
16.4	0.9932	0.0408	0.0142	0	0.9918	0.17	1
17.7	0.9928	0.0401	0.0130	0	0.9919	0.11	1
21.8	0.9909	0.0385	0.0112	0	0.9896	0.12	1
23.5	0.9902	0.0365	0.0095	0	0.9882	0.17	1
31.4	0.9869	0.0334	0.0067	0	0.9809	0.31	1
40.2	0.9832	0.0319	0.0047	0.0001	0.9774	0.26	0.9999
59.3	0.9753	0.0308	0.0033	0.0006	0.9647	0.32	0.9995
78.6	0.9672	0.0312	0.0036	0.0020	0.9502	0.38	0.998

FIG. 3.7. Measured thermal conductivity of glass fiber material.

Using equation (3.6) (and noting that $\lambda_G = \lambda - \lambda_e$), equation (3.7) and the additional expression for λ_F

$$\lambda_F = \alpha \cdot (1 - \varepsilon_p) \cdot \lambda_s$$

it is possible to calculate the parameters α, ε_S and ε_P. The result of this calculation is given in the last three columns in FIG. 3.7 and for α and ε_S in FIG. 3.8 and 3.9 as well. α and ε_S conform to straight lines including points (1,0) and (1,1) respectively.

In this way the structural parameter α (FIG. 3.8), ε_S (FIG. 3.9) and ε_P (equation (3.7)) have been established as a function of the porosity.

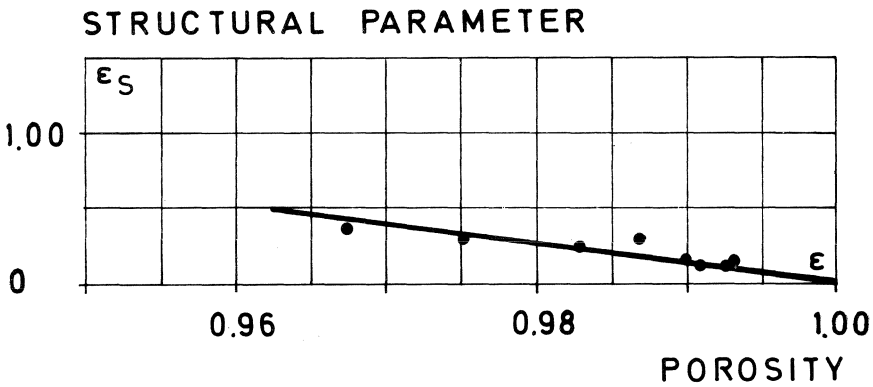

FIG. 3.8. The structural parameter α as a function of porosity.

● measured values

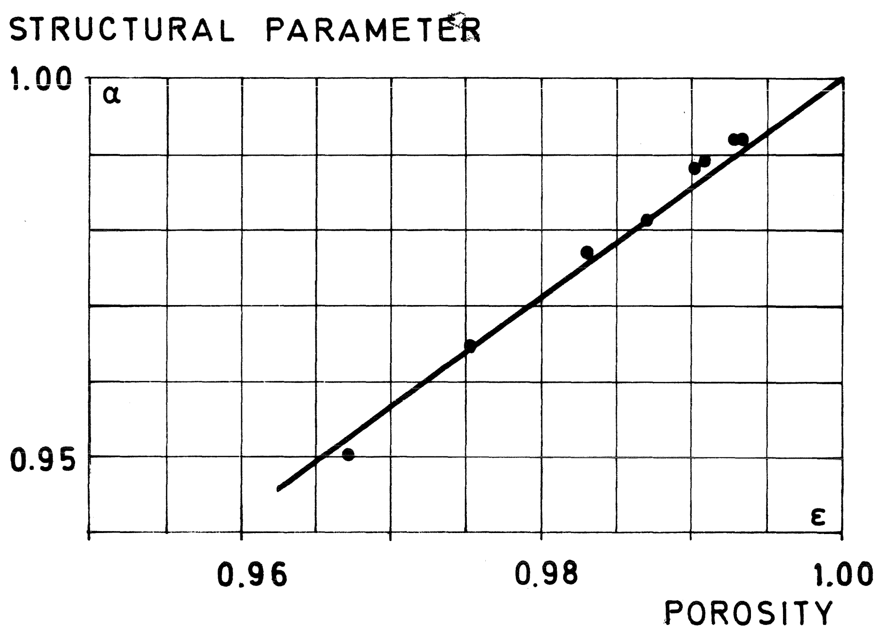

FIG. 3.9. The structural parameter ε_S as a function of porosity.

● measured values

4 HEAT TRANSFER IN A FIBROUS MATERIAL.

4.1 Introduction.

A discussion of the different mechanisms of heat transfer in a fibrous material will be presented in the following sections. Comparisons will be made between the theoretical model and the experimentally established behaviour of a glass fiber insulation. Even if the detailed quantative results are only applicable for the investigated material, the qualitative analysis is valid for any fiber insulation. Making the same investigations in order to find the mechanisms of heat transfer in a fibrous insulation of a special make involves no additional difficulties - provided that suitable measuring equipment is available. (The symbols have been explained in preceding sections and are assembled under the heading Nomenclature.)

4.2 Heat transfer due to conduction in solids and radiation.

The effective thermal conductivity due to radiation and conduction in solids that is the thermal conductivity of the evacuated material, can be calculated from

$$\lambda_e = \lambda_F + \frac{4 \cdot \sigma_s \cdot L_o \cdot T_m^3}{\left(\frac{1}{\beta} + \frac{L_o}{d}\left(\frac{2}{\Sigma_o} - 1\right)\right)} = \lambda_F + \lambda_R \tag{4.1}$$

λ_F is given in FIG. 3.7 and β in FIG. 3.6. L_o is calculated from

$$L_o = \frac{\pi}{4} \cdot \frac{D}{1 - \varepsilon} \tag{4.2}$$

The influence upon the radiation of the emissivity of the boundary surfaces and the thickness of specimen was neglected in the previous treatment. FIG. 4.1 illustrates this influence on the λ_R-value for the investigated material with high porosity (when the porosity decreases this influence becomes less marked). As seen from the figure the λ_R-value will be underestimated if the specimen is too thin and the emissivity of the surfaces is small. In the guarded hot plate used $\Sigma_o \simeq 0.95$ and the thickness is

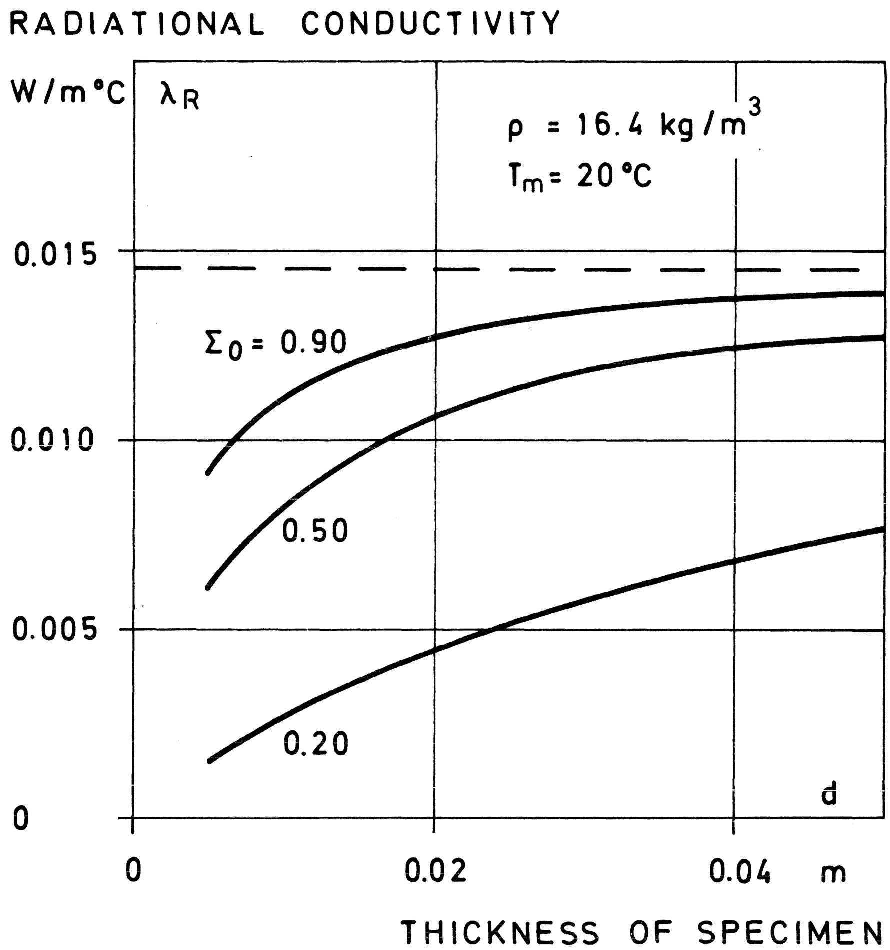

FIG. 4.1. The influence of emissivity of boundary surfaces and thickness of specimen upon radiation.

0.04 m of the high porosity specimen. The error introduced by neglecting the boundary surfaces is acceptable.

It is obvious, however, that if measurements are conducted on thin specimens or if the emissivity of the boundary surfaces is small, then the full expression for radiation in equation (4.1) has to be used.

The radiation coefficient β for the investigated fiber insulation was found to increase with increasing temperature and increasing porosity, which is logical from the physical point of view. These general observations were also made by Verschoor & Greebler (1952). Pelanne (1968) found a linear relationship between porosity and a radiation coefficient in experiments on fiber insulation. These measurements were only performed at one temperature. The present investigation gives β as a linear function of porosity as well as temperature in the intervals of porosity and temperature, which were studied.

The effective thermal conductivity due to conduction in solids λ_F, was found to be neglegible at high porosities and of increasing importance as the porosity decreases. Assumptions have previously been made that solid conduction contributes to the total thermal conductivity in direct proportion to the volume fraction of fiber present (Verschoor & Greebler, 1952; Andersen, 1968) or that this contribution can be neglected completely.

The effective thermal conductivity of the evacuated material can be calculated from equation (4.1). This is shown in FIG. 4.2-4.4 where comparisons are made with measured values. As can be seen from these figures the measured points conform well to the calculated lines describing the behaviour of the fibrous insulation in the studied temperature and porosity range. FIG. 4.5 shows the influence of the different mechanisms of heat transfer upon the evacuated material at 20°C.

4.3 Heat transfer due to conduction in gas.

The effective thermal conductivity due to conduction in gas may

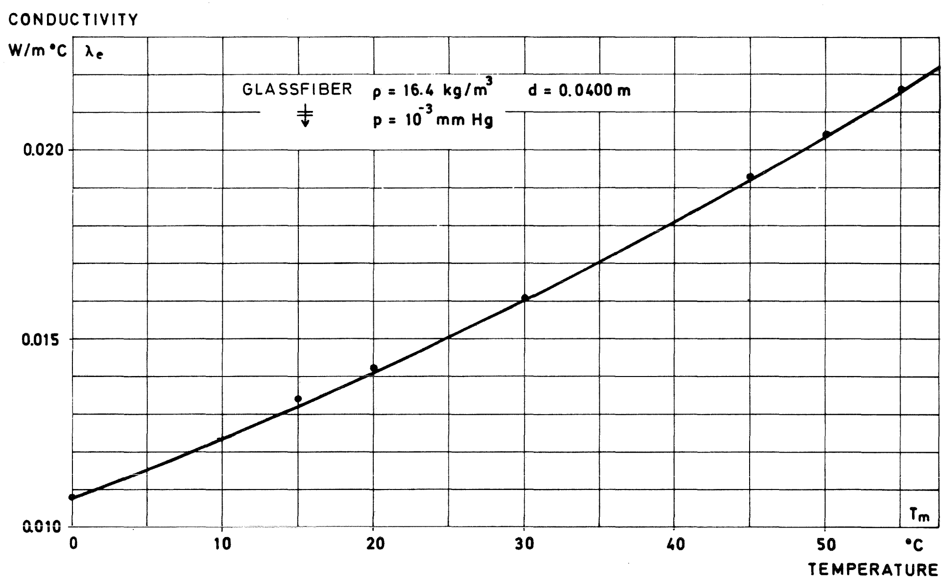

FIG. 4.2. Thermal conductivity of evacuated specimen as a function of mean temperature.

— eq. (4.1) ● measured values

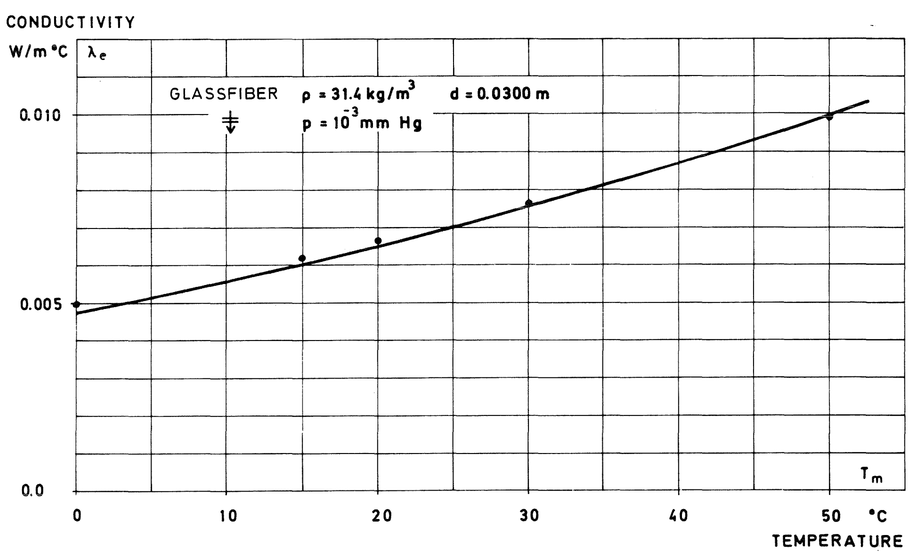

FIG. 4.3. Thermal conductivity of evacuated specimen as a function of mean temperature.

— eq. (4.1) ● measured values

4.4.

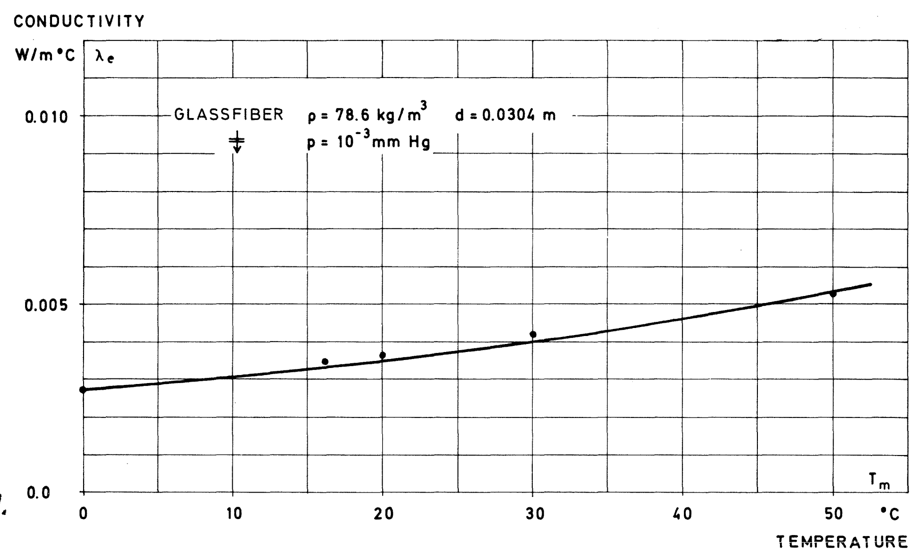

FIG. 4.4. Thermal conductivity of evacuated specimen as a function of mean temperature.

— eq. (4.1) ● measured values

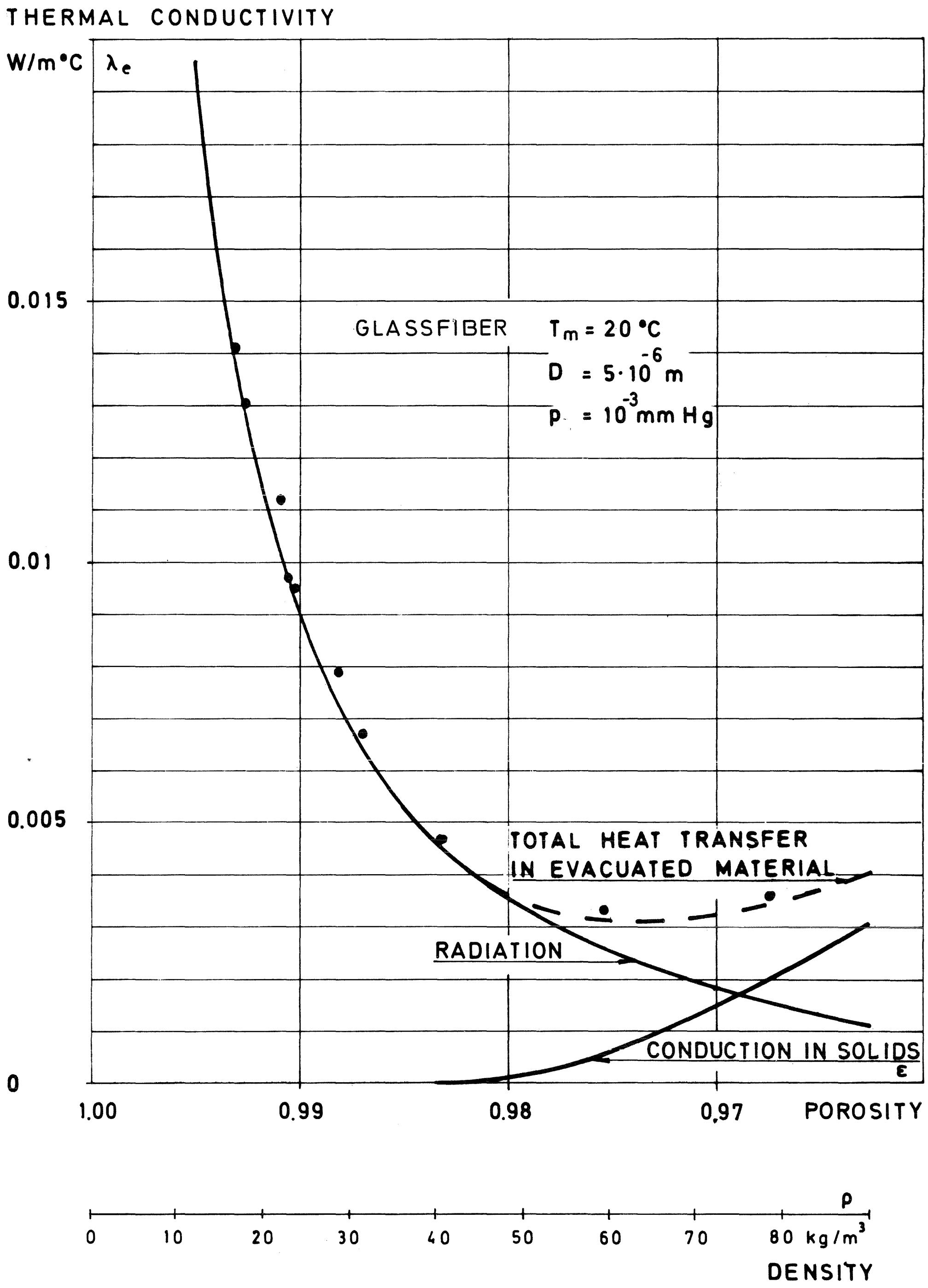

FIG. 4.5. The mechanisms of heat transfer in the evacuated material.

— eq. (4.1) ● measured values

be written

$$\lambda_G = \alpha\cdot \varepsilon_P\cdot \lambda_g + (1 - \alpha)\cdot \frac{\lambda_s\ \lambda_g}{\varepsilon_S\cdot \lambda_s + (1 - \varepsilon_S)\cdot \lambda_g} \qquad (4.3)$$

and

$$\varepsilon = (1 - \alpha)\cdot \varepsilon_S + \alpha\cdot \varepsilon_P$$

α is given in FIG. 3.7 and ε_S in FIG. 3.9.

If the pressure of the gas is reduced, then the thermal conductivity of the gas λ_{ge} should first be calculated from

$$\lambda_{ge} = \lambda_g \frac{pL_o}{pL_o + E\ T} \qquad (4.4)$$

and then inserted into equation (4.3). L_o can be calculated from equation (4.2).

The influence of the structural parameters is most easily explained by referring to FIG. 2.5. As the porosity increases, α approaches one, which means that an increasing part of the volume is oriented in parallel to the direction of heat flow. At the same time, however, ε_S decreases to zero, and for this reason the thermal conductivity due to series orientation may still be considerable. To emphasize this further, it can be pointed out, that the theoretical structure which will give the largest contribution from conduction in gas to the thermal conductivity is found when $\varepsilon_S \rightarrow 0$, that is

$$\lambda_{G\ max} = \varepsilon\cdot \lambda_g + (1 - \alpha)\cdot \lambda_s$$

Even if α is close to one the second part of this equation may be of importance.

The effective thermal conductivity of the unevacuated and partly evacuated material can be calculated by $\lambda = \lambda_G + \lambda_e$. This has been done for the investigated fibrous insulation in FIG. 4.6 and 4.7. These figures show that the calculated values describe the measured behaviour of the material. This means that equation (4.4) describing the influence of reduced pressure is valid

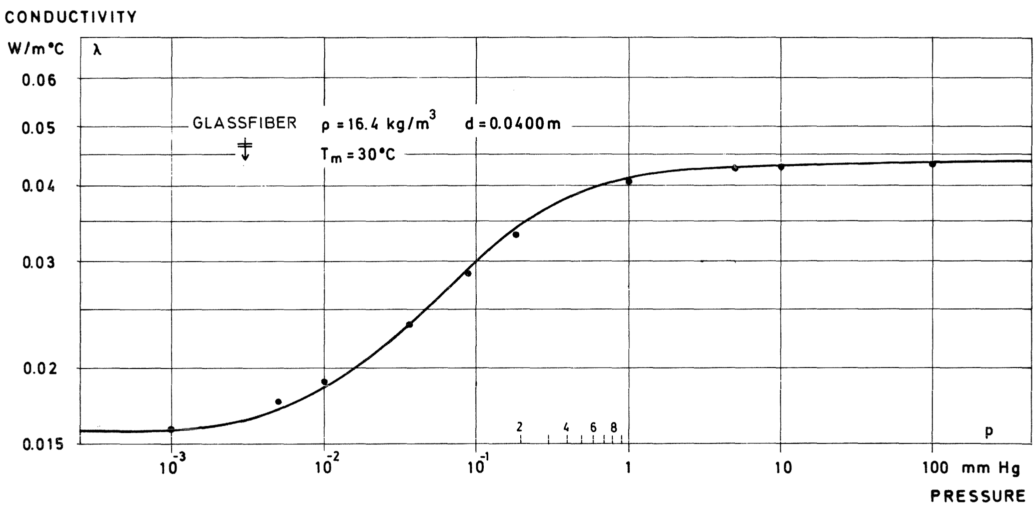

FIG. 4.6. The influence of air pressure on the thermal conductivity of a fibrous material.

— eq. (4.1)-(4.4) ● measured values

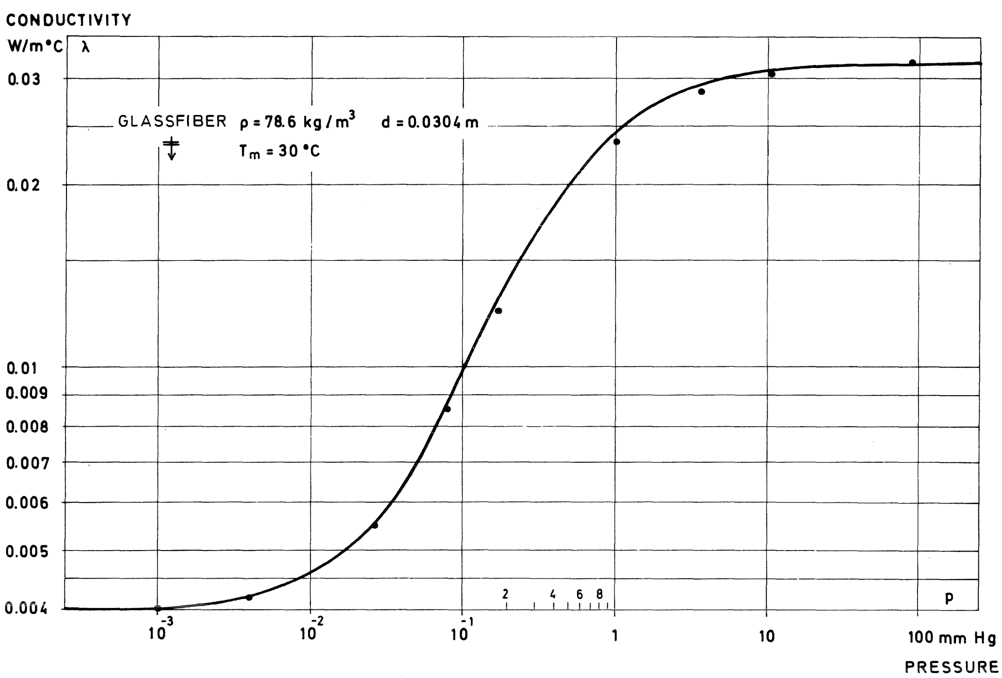

FIG. 4.7. The influence of air pressure on the thermal conductivity of a fibrous material.

— eq. (4.1)-(4.4) ● measured values

which in turn means that the equation (4.2) giving the mean distance between fibers is correct. This also means that the whole of equation (4.3) has to be taken into consideration. It is not possible to neglect any part of this equation as has earlier been done (cf. the references in section 2.2). Such simplifications will lead to underestimation of the influence of conduction in gas and then to misinterpretation of the mechanisms of heat transfer in the material. Verschoor & Greebler (1952) attributed the difference between simplified theories and measurements to convection. This explanation was also used by Arroyo (1967) and by Tye & Pratt (1969). Christiansen & Hollingsworth (1958) mentioned convection as one explanation, but also pointed out that the gas interacts with the fibers. Mumaw (1968) attributes the same difference to the influence of binder on the porosity of the material, while Pelanne (1968) explains it as an unidentified interaction between air and other modes of heat transfer.

FIG. 4.8 illustrates the influence of gas pressure upon the thermal conductivity in a material at different temperatures. The differences in thermal conductivity for the evacuated material at different temperatures depend upon the influence of radiation. This difference increases slightly for the unevacuated material since the influence of temperature upon the gas is added.

The influence of the mean distance between fibers is shown in FIG. 4.9. The figure illustrates the behaviour of the material at a mean distance between fibers, calculated according to equation (4.2) and if L_o is assumed to be less or greater than this calculation.

E in equation (4.4) depends upon the mean free path of the gas according to section 2.3. Normally the gas is air. FIG. 4.10 illustrates the influence of different gases (cf. Wilson, 1957).

The influence of convection in the material has thus far not been considered. In open pore material the fields of gravity and temperature may lead to flow of gas if they counteract one another and the porosity of the material is sufficiently high.

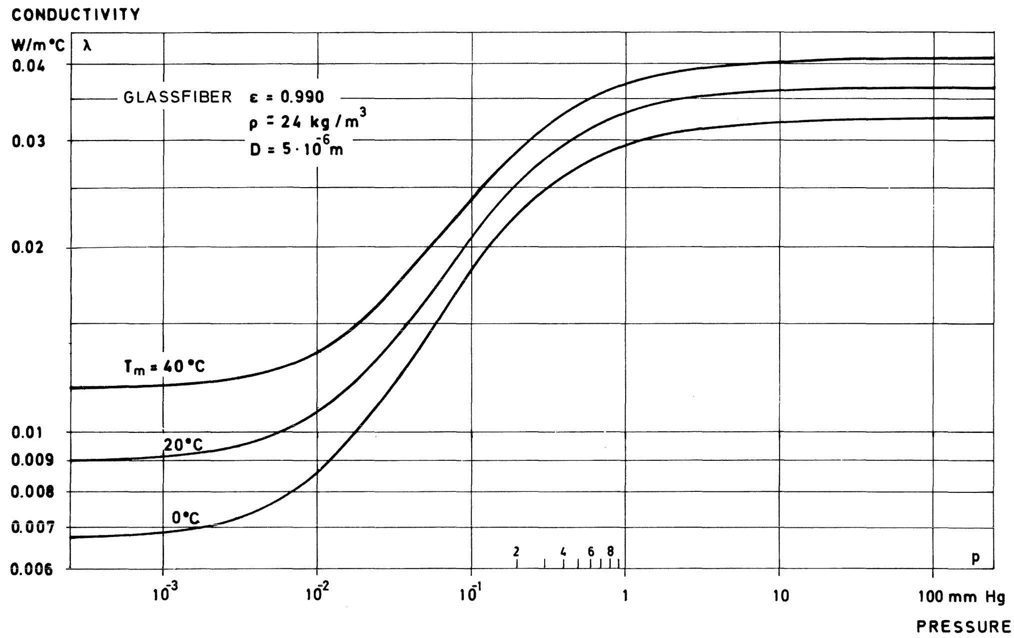

FIG. 4.8. The influence of temperature and pressure on the thermal conductivity of a fibrous material.

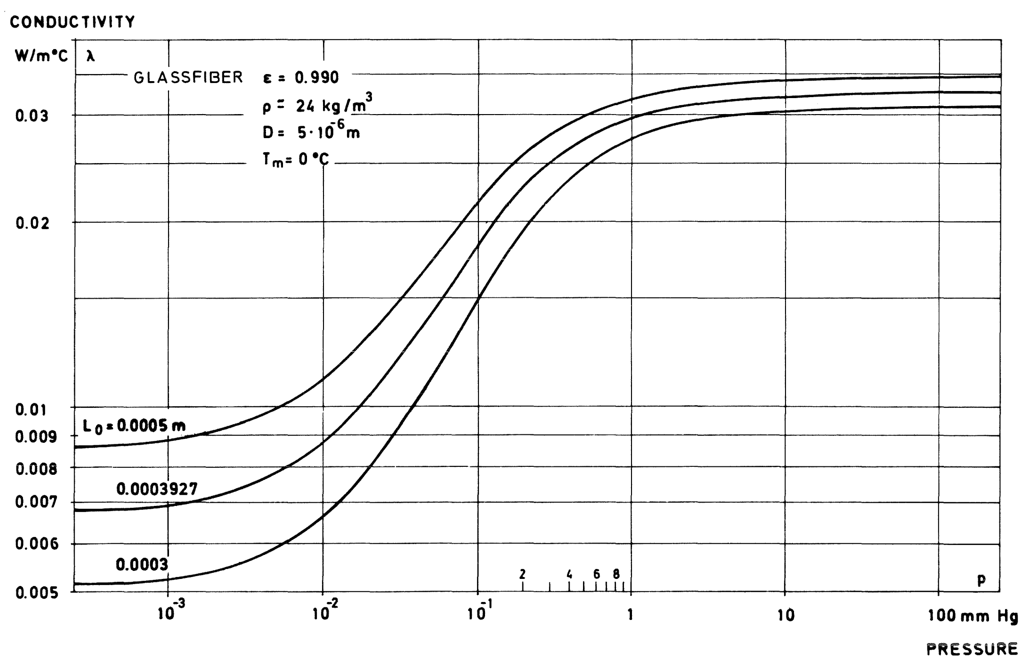

FIG. 4.9. The influence of mean distance between fibers and pressure on the thermal conductivity of a fibrous material.

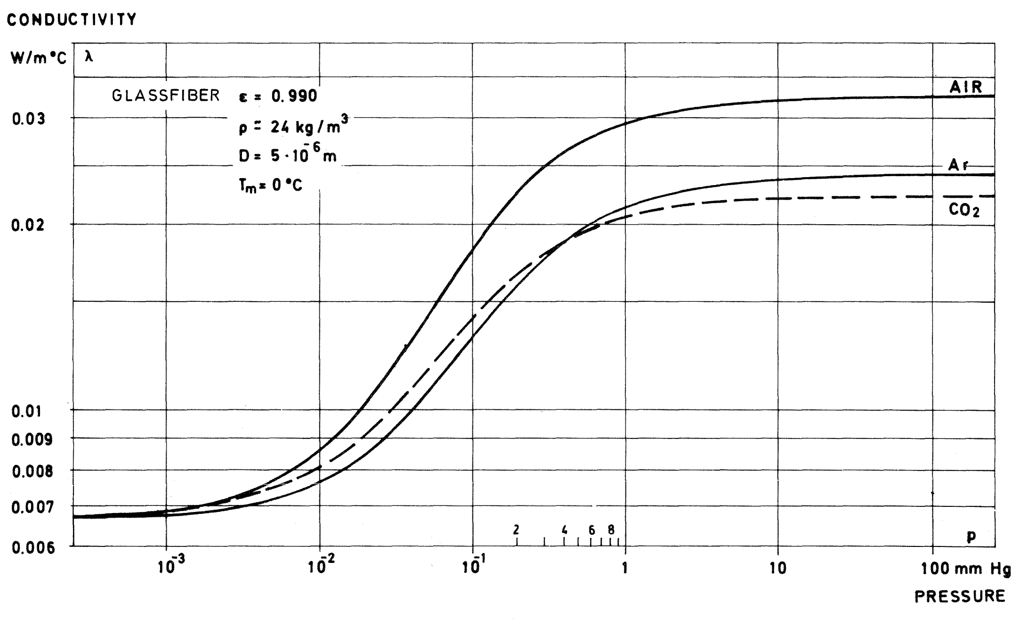

FIG. 4.10. The influence of gas type on the thermal conductivity of a fibrous material.

In the measurements the orientation of the heat flow was generally unidirectional to the field of gravity and no convection was present. In order to investigate the influence of direction of heat flow, measurements were made on the high porosity specimen at different temperature-differences and with the hot side alternatingly above and below the specimen. The result of this investigation is shown in FIG. 4.11. It is obvious that no convection is present. This result can also be calculated theoretically, but the problem of natural convection will be treated elsewhere (Bankvall, 1971/72). The concept of convection is sometimes regarded as the diffusion of gas molecules due to concentration gradients in the temperature field. This type of convection is of little significance and can be neglected completely in the present investigation (cf. Mumaw, 1968).

The effective thermal conductivity due to conduction in gas is consequently given by equation (4.3), and it is possible to calculate the total effective thermal conductivity of the fibrous insulation as $\lambda = \lambda_G + \lambda_e$. FIG. 4.12-4.14 give the results of such calculations compared to measured values of the thermal conductivity as a function of temperature. The measured values agree well with the calculated curves.

4.4 The total effective thermal conductivity of a fibrous material.

The total thermal conductivity of a fibrous material is a result of conduction due to gas, conduction due to solid phase and radiation in the material, that is

$$\lambda = \lambda_G + \lambda_F + \lambda_R \qquad (4.5)$$

or

$$\lambda = \alpha \cdot \varepsilon_P \cdot \lambda_g + (1 - \alpha) \cdot \frac{\lambda_s \lambda_g}{\varepsilon_S \cdot \lambda_s + (1 - \varepsilon_S) \cdot \lambda_g} + \alpha (1 - \varepsilon_P) \cdot \lambda_s +$$

$$+ \frac{4 \cdot \sigma_s \cdot L_o \cdot T_m^3}{\left(\frac{1}{\beta} + \frac{L_o}{d} \left(\frac{2}{\Sigma_o} - 1\right)\right)} \qquad (4.6)$$

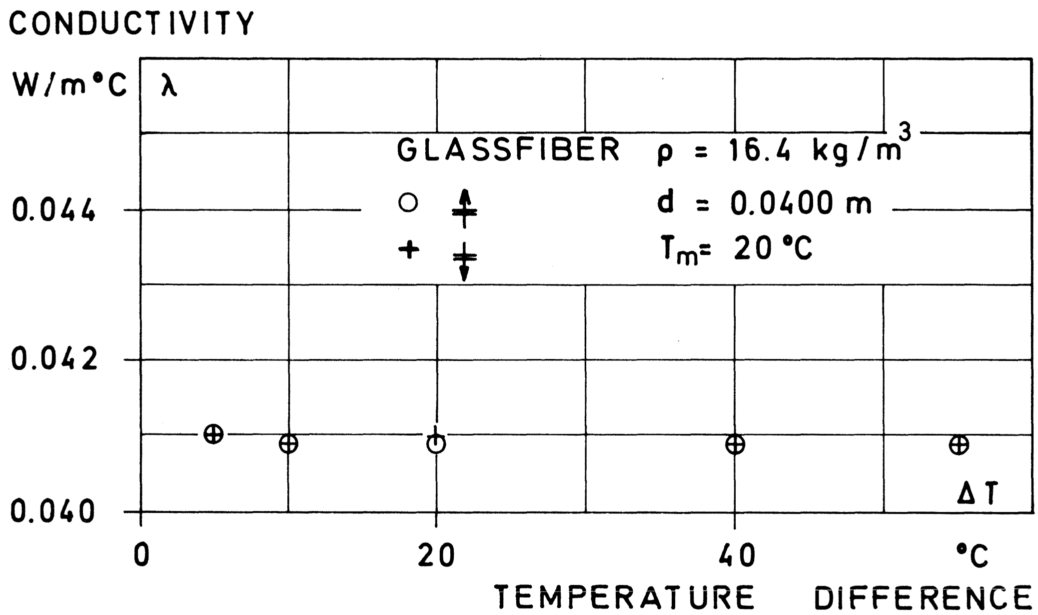

FIG. 4.11. The influence of direction of heat flow and temperature difference on the thermal conductivity of a fibrous material.

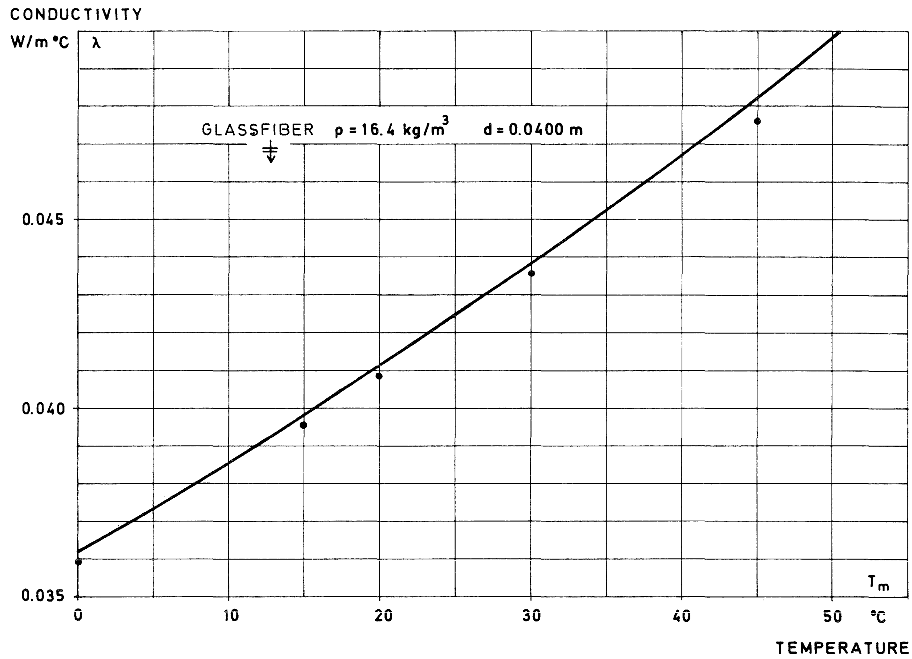

FIG. 4.12. The total thermal conductivity of a fibrous insulation as a function of mean temperature.

— eq. (4.1)-(4.3) ● measured values

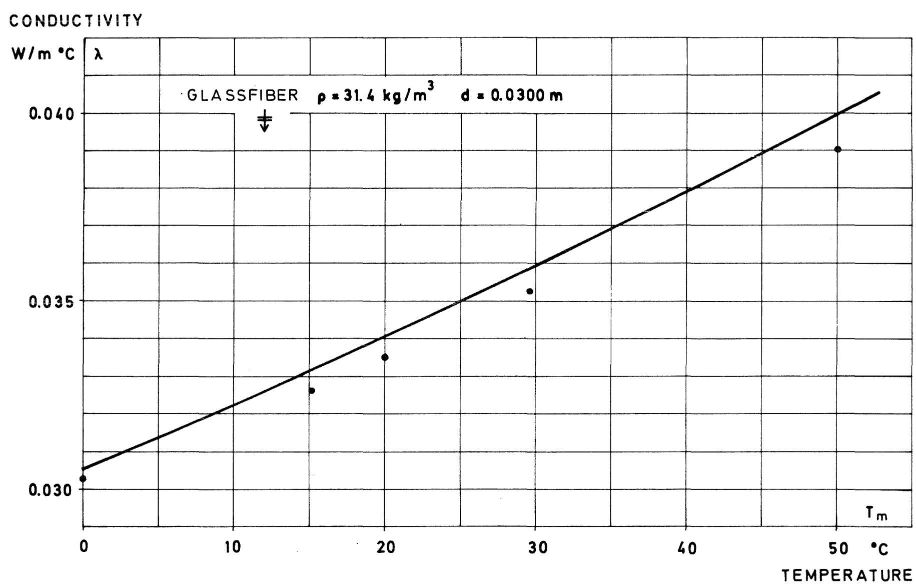

FIG. 4.13. The total thermal conductivity of a fibrous insulation as a function of mean temperature.

— eq. (4.1)-(4.3) ● measured values

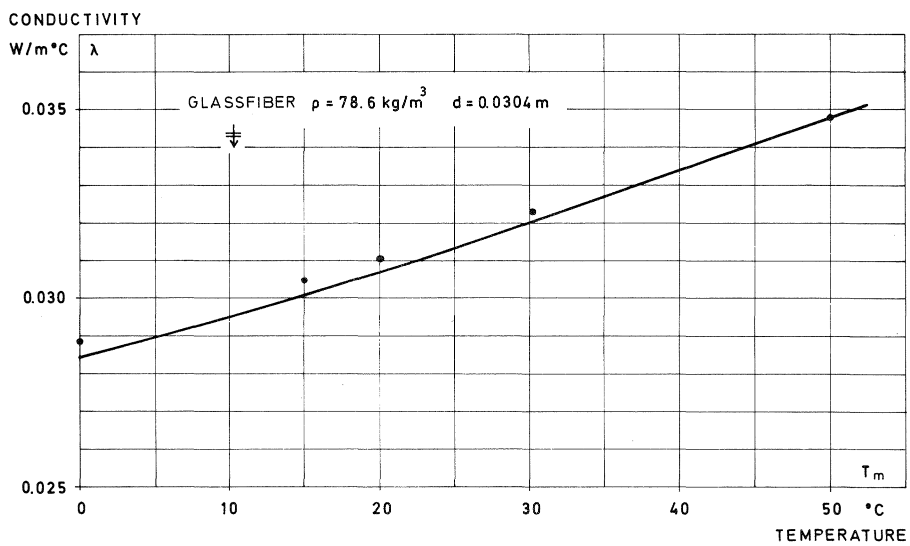

FIG. 4.14. The total thermal conductivity of a fibrous insulation as a function of mean temperature.

— eq. (4.1)-(4.3) ● measured values

These equations describe the mechanisms of heat transfer in the fibrous material as discussed in detail in the preceding sections, from which it is possible to calculate the behaviour of the material.

FIG. 4.15 shows the influence of temperature on the thermal conductivity of the material. The figure shows that this influence is greatest at high porosities where radiation is predominant.

The contribution of the different mechanisms of heat transfer to the total thermal conductivity of the insulation is shown in FIG. 4.16. It is seen that the most important factor is conduction in gas, and it should be noted that though the thermal conductivity of the free air at this temperature is 0.0257 W/m^oC its contribution in the mateial is about 0.0275 W/m^oC (the reason for this has been explained in this report). At high porosities the radiation is considerable but decreases as the density of the material increases. The influence of conduction in solids is negligible at low densities, but increases as the density increases. In combination with the decreasing radiation, this gives a minimal thermal conductivity of the material.

The influence of temperature on the different mechanisms of heat transfer is illustrated in FIG. 4.17 for two different porosities. These figures show the increase of the thermal conductivity with temperature due to radiation and conduction in gas. The influence of temperature upon the conduction in solids has been neglected (the chemical composition of the fibers indicates a 6 % variation of λ_F in the interval studied). Because of the mechanisms of heat transfer, the total thermal conductivity is more influenced by temperature when porosity is high, that is in low density materials.

The influence of the mechanisms of heat transfer on the effective thermal conductivity of the fibrous material can be summarized as follows

- conduction due to gas contributes the largest part of the thermal conductivity in the range of density studied (15 - 80 kg/m^3)

- radiation is of greatest importance for low density materials and leads to high values of thermal conductivity in these cases.

- conduction in solids is important in high density materials where it can lead to an increase in the thermal conductivity value.

- increasing mean temperature of a material gives an increase in its thermal conductivity value. This is especially noticeable at low densities due to radiation.

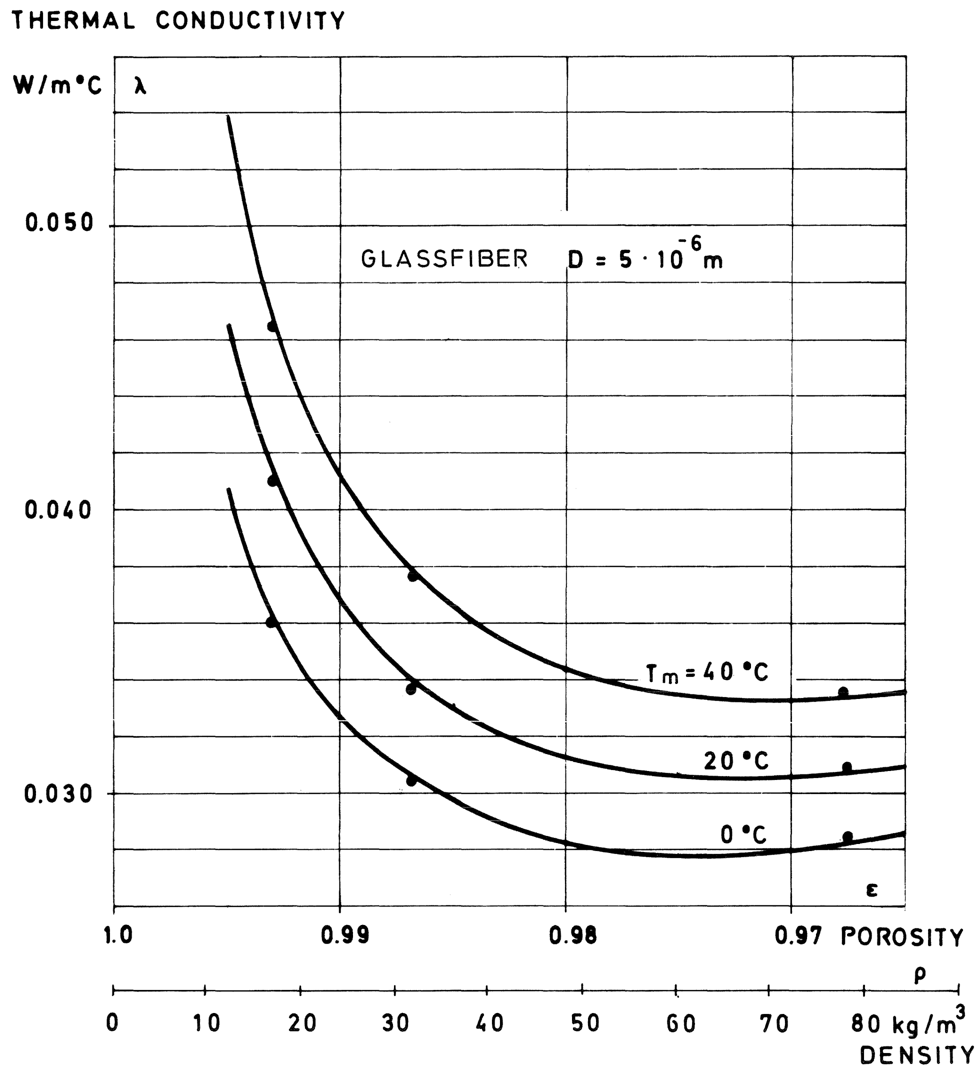

FIG. 4.15. The influence of temperature on the thermal conductivity of fiber insulation.

—— eq. (4.1)-(4.3) ● measured values

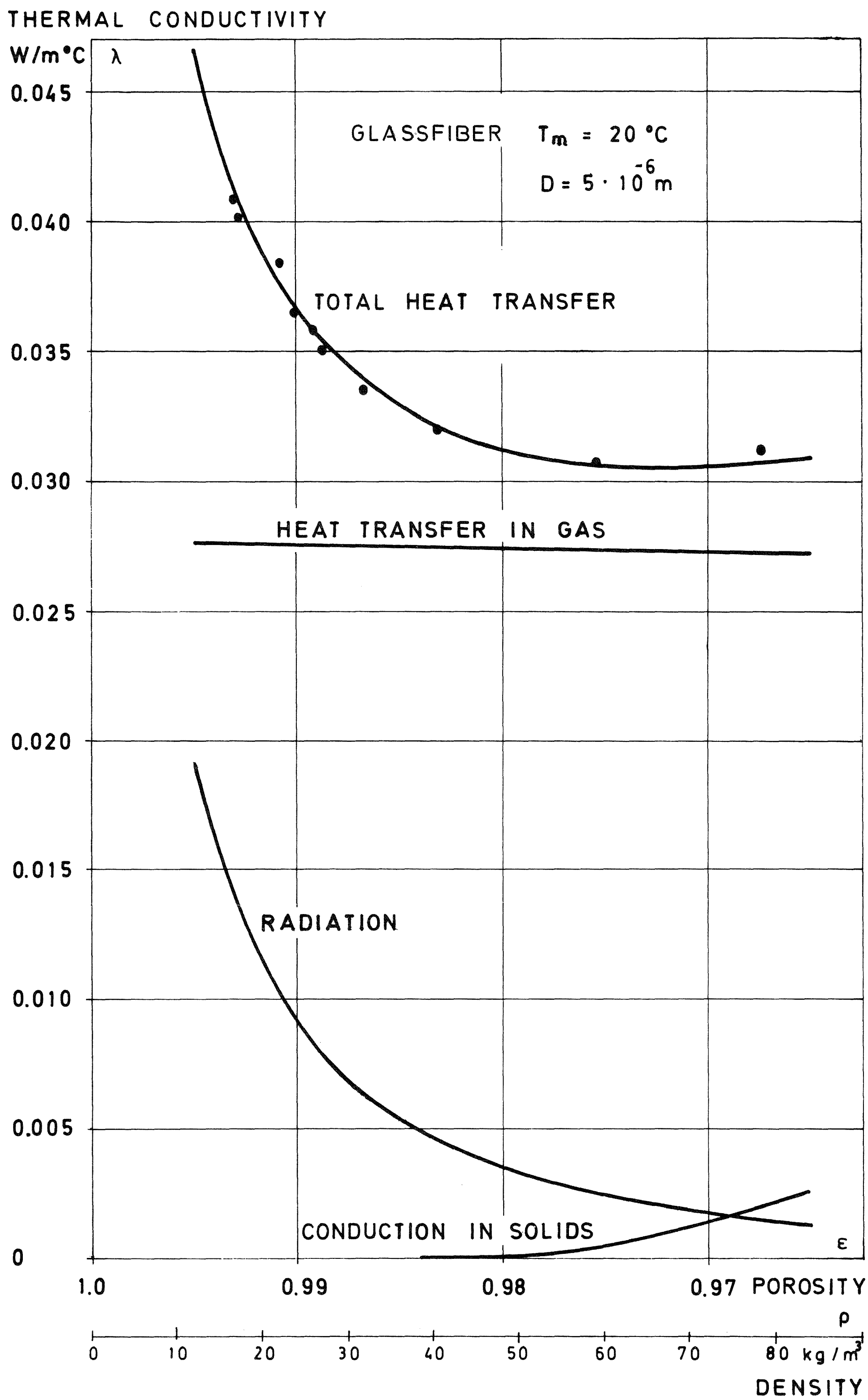

FIG. 4.16. The mechanisms of heat transfer in a fibrous material.

— eq. (4.1)-(4.3) ● measured values

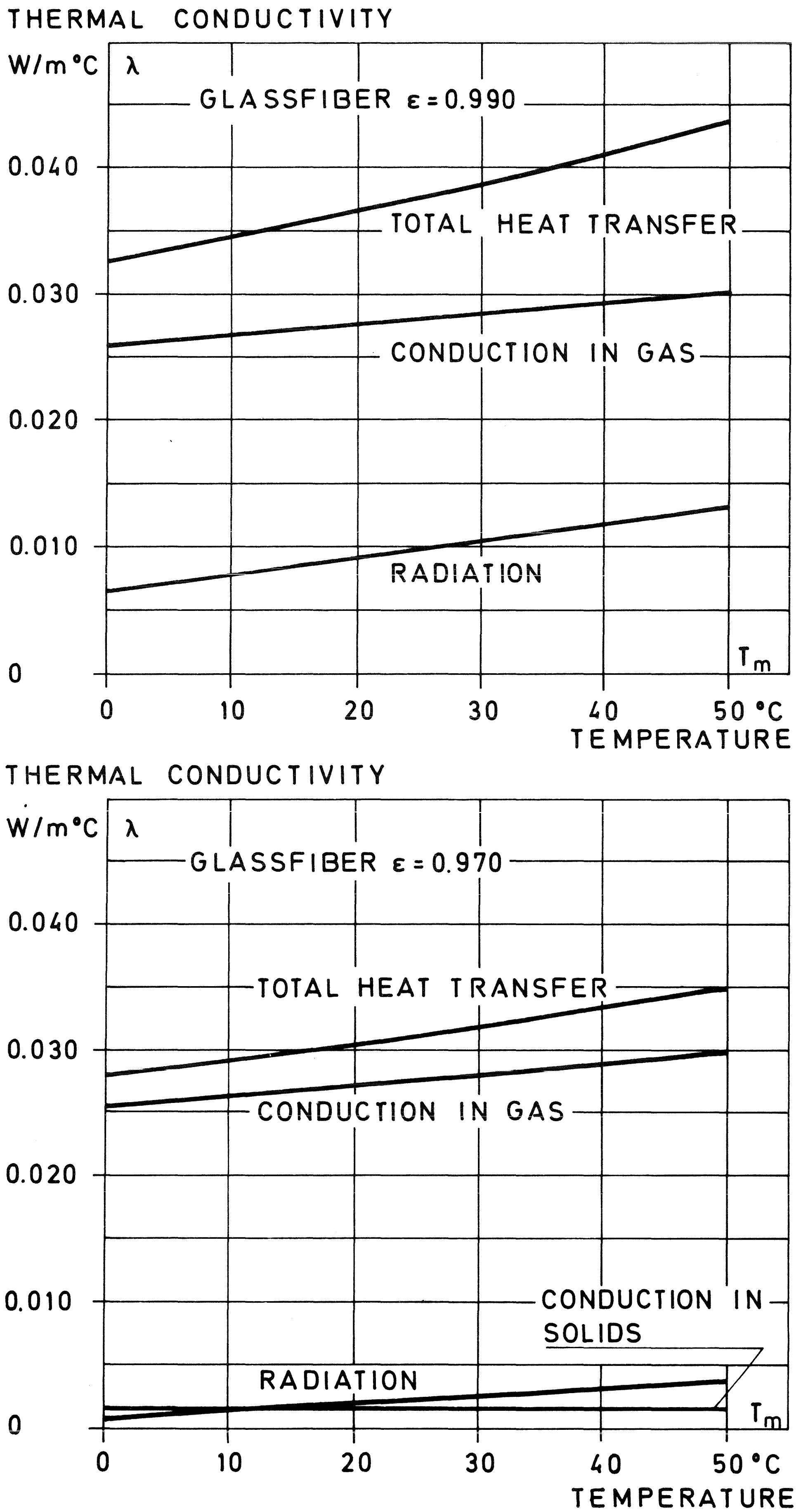

FIG. 4.17. The influence of temperature on the heat transfer mechanism.

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