Effect of porosity on thermal conductivity of porous materials

Abstract. The basic idea of porous materials has been used in different applications of engineering science especially regards to thermal insulation. In this study the effect of porosity on thermal conductivity has been investigated experimentally by using Cylindrical thermal probe (TP02® Hukseflux). During transmission the heat power in the probe, the temperature is variation as a function of the natural logarithm. The slope of the graph is representing the proportion inverse to the thermal conductivity. Different materials in terms of porosity have been selected to identify influence of porosity on thermal conductivity. At first fluid material (glycerol) with no porosity, and after that glass beads of different diameters to introduce the porosity and different types of glass wool as an example of insulation materials. Comsol Multiphysics® axisymmetric module 2-D has been used to validate the experimental results.

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1. Introduction
The structure of the porous materials consists of solid and the pores which are filled with air or others gases. The basic idea of porous materials has been used in different applications of engineering science especially regards to thermal insulation. Insulation materials are used to reduce heat loses and to provide environment comfortable for human. Some porous materials such as vermiculite used to reduce costs and to increase compressive strength of insulation materials [1].
Different studies [2], [3] and [4] are assume heat transfer in porous materials occur due to the conduction and ignore the convection and radiation. Therefore, the thermal conductivity of a porous materials is often called equivalent or effective thermal conductivity. Most porous materials have a pore size less than 10 mm, therefore effect of radiation and convection in these materials is negligible compared to conduction [4].
Heat transmit in porous materials due to the conduction can be described by Fourier’s Law, which depends on the thermal conductivity and variation of temperature across the thickness of the porous materials. This law assumed that the thermal conductivity of the materials is isotropic according to the expression:

\[ q = -K \frac{dT}{dx} \]  

(1)

Where
\( q \) : heat flux, (W/m²)
\( dT/dx \) : temperature gradient across a material (K/m)
\( K \) : effective thermal conductivity of a material. (W/mK)
The porous materials contain closed and open pores. Due to transfer the air into pores, the convection will occur and tends to increase thermal conductivity of these materials [5]. The first analytical models has been proposed in 1960 by Meredith and Tobias to predict thermal conductivity of porous materials [6]. They mentioned that the volume fraction affects on the thermal conductivity of a two-component material because this factor is change by the size distribution and arrangement of particles of two-component porous materials. Zhang and Liang in 1995 studied two different solid materials mixed together and they referred also to the effect of volume fraction on the thermal conductivity [7]. The heat flow that used in there study was transfer from top to below and parallel to the gravity. Yi et al. in 2003 investigated the effect of the diameter of particles of porous on thermal conductivity of foams [8]. They explained that the diameter of the pore had a miner effect on thermal conductivity. The relating porosity with thermal conductivity of construction materials has been proposed by Bhattacharjee and Krishnamoorthy in 2004 [9]. They use cubic pores to conclude thermal conductivity of porous materials. The effect of porosity on thermal conductivity is studied by Lafdi et al. in 2007 [10], where they used aluminum foams as porous material. They conclude that porosity and pore size have big impact on thermal conductivity. In this study the effect of porosity on thermal conductivity has been investigated experimentally by using Cylindrical thermal probe (TP02® Hukseflux).

2. Theory of the thermal probe

Theory of the thermal probe depends on sending a heat flow with constant power and variable temperature. Thermal conductivity can be calculated from the slope value \( Q/4\pi \lambda \) in equation (2):

\[
\lambda = \frac{Q}{4\pi} \left[ \ln\left(\frac{t_2}{t_1}\right) \right]
\]

Equation (2) depends on the basic equation (3) for Carslaw and Jaeger [11]:

\[
\Delta T = -\frac{Q}{4\pi \lambda} Ei\left[\frac{r^2}{4\alpha t}\right]
\]

For fluid materials (no porosity) such as Glycerol, the variation of temperature with the time is linear, thus equation 2 can be applied directly to find thermal conductivity. This variation becomes non-linear for insulation material (existence porosity) so best straight line on the curve can be chosen to determine thermal conductivity.

For initial time (short time \( < t_{\text{min}} \)), thermal properties of the probe and contact with the materials affected on this period. This time is described by Vos [12] as expression:

\[
t_{\text{trans}} = \frac{50(R_s)^2}{4\alpha}
\]

where \( R_s \) is the radius of the probe.

When the heating waves reaches to the end on materials, the nonlinearity behaviours attributed to the axial losses. Vos [12] expressed this time by:

\[
t_{\text{max}} = \frac{0.6(r-R_s)^2}{4\alpha}
\]

Where \( r \) is the sample radius, \( R_s \) is the radius of the probe and \( \alpha \) thermal diffusivity \([\text{m}^2/\text{s}]\)
3. The experimental programme

3.1. Porosity

Efficiency of insulation materials is affected by the porosity. The porosity has been investigated for different materials from the fluid materials such as Glycerol to solid porous materials (glass wool and rock wool).

For glass beads, two different diameter of glass beads (2 mm and 10 mm) have been selected to study the effect of porosity on thermal conductivity by using probe method (figure 2 and figure 3).

| Figure 2. Glass beads 2 mm diameter | Figure 3. Glass beads 10 mm diameter |
|-------------------------------------|-------------------------------------|

The density of glass beads have been measured and porosity has been calculated by water saturation method. The results of porosity of glass beads are shown in table 1 below:

| Table 1. Experimental results for porosity of Glycerol |
|------------------------------------------------------|
| Density [kg. m⁻³] | Porosity [%] |
|-------------------|--------------|
| Glass beads 2 mm  | 1530         | 36.5         |
| Glass beads 10 mm | 1470         | 41.0         |
For insulation materials, two different type of insulation materials have been selected glass wool and rock wool; to investigate the porosity. Helium pycnometer (Accupyc 1330) has been used to determine porosity of the glass wool [14]. Flow resistivity method used to calculate porosity of rock wool [15]. The results of the porosity of the glass wool and rock wool are shown in table 2 below.

|          | Density [kg m⁻³] | Porosity [%] |
|----------|-----------------|--------------|
| Glass wool | 69              | 97.4 [14]    |
| Rock wool | 100             | 92.6 [15]    |

3.2. Thermal conductivity
All tests have been carried out by probe of Hukseflux ©. The probe Hukseflux® TP02 has a length 150 mm with diameter of 1.5 mm, it consists of different layers in the radial direction (Constantan 0.065 mm, Glass pearl 0.355mm and Stainless steel 0.42 mm). During the experimental test, different materials have been choose according to the different rate of porosity.

3.2.1 Glycerol. At first and to calibrate TP02 probe Hukseflux®, thermal conductivity of Glycerol has been investigated. This fluid has known thermal properties (thermal conductivity: 0.29 W/ mK and diffusivity: 9.10⁻⁸ m²/s) and It does not have porosity.

Variation of temperature with natural logarithm time for glycerol is linear and equation (2) can be applied to find thermal conductivity from the slope value \(Q/(4πλ)\). The experimental value by using TP02 probe Hukseflux is consistent with the reference value for with time test 180 s (table3).

|          | Test time [s] | 60   | 120  | 180   | 240   |
|----------|---------------|------|------|-------|-------|
| Thermal conductivity [W (mK)⁻¹] | 0.30±3%       | 0.30±3% | 0.29±3% | 0.28±3% |
3.2.2 Glass bead. All tests have been carried out in plastic tube of 4 mm thickness and 10 cm diameter by probe of Hukseflux ®. The probe TP02 inserted in the center of the samples vertically (figure 5 and figure 6). Low heat power (0.87 W/m) has been selected in the experimental tests with time (600s) controlled by the TPSYS02 interface to obtain the curve of variation of the temperature with the logarithm time.

![Figure 5. Image of 2 mm glass beads during the test by TP02](image1)

![Figure 6. Image of 10 mm glass beads during the test by TP02](image2)

For 2 mm diameter glass beads, a linear curve is obtained but, non-linear S-shaped curve is observed for glass diameters 10 mm (Figure 7). Thermal conductivity for glass beads 2 mm diameter can be calculated directly from applying equation (2) but for 10 mm the best line between $t_{\text{trans}}$ and $t_{\text{max}}$ must be selected to measure thermal conductivity from the slope value $(Q/4\pi \lambda)$. Due to the air between particles and thermal inertia contrasts, thermal conductivity is represented equivalent thermal conductivity.

![Figure 7. Variation of temperature against natural logarithm of time for glass beads](chart)

For 2 mm diameter glass beads, a linear curve is obtained but, non-linear S-shaped curve is observed for glass diameters 10 mm (Figure 7). Thermal conductivity for glass beads 2 mm diameter can be calculated directly from applying equation (2) but for 10 mm the best line between $t_{\text{trans}}$ and $t_{\text{max}}$ must be selected to measure thermal conductivity from the slope value $(Q/4\pi \lambda)$. Due to the air between particles and thermal inertia contrasts, thermal conductivity is represented equivalent thermal conductivity.
The experimental value for thermal conductivity of glass beads by using TP02 probe Hukseflux is close to the reference value [16] and [17] for low flow (0.87 W.m$^{-1}$) and time test 600 s (table 4).

| Glass beads 2 mm | 0.18 |
|------------------|------|
| Glass beads 10 mm| 0.09 |

Table 4. Experimental results for thermal conductivity [W (mK)$^{-1}$] of glass beads

3.2.3 Insulation materials. Two different samples insulation materials have been selected to study thermal conductivity by using TP02 Hukseflux ® probe: glass wool with density 69 kg.m$^{-3}$ and rock wool with density 100 kg.m$^{-3}$ are chosen (figure 8 and figure 9). Low flow (0.87 W.m$^{-1}$) with time (1500s) have been selected during the test by TP02 to study the effect of structure of materials on thermal conductivity.

![Figure 8. Image of glass wool during the test by TP02.](image1)

![Figure 9. Image of rock wool during the test by TP02.](image2)

The variation of temperature for each the glass wool and rock wool are approximately the same due to the structure of the fibrous of materials but thermal conductivities are different because there is variation in the values of densities and porosities (table 5).

| Glass wool  | 0.033 |
|-------------|-------|
| Rock wool   | 0.037 |

Table 5. Experimental results for thermal conductivity [W (mK)$^{-1}$] of insulation materials

4. COMSOL Multiphysics® simulation

Comsol Multiphysics® software has been used to validate the experimental tests and axisymmetric module 2-D was chosen to represent the Hukseflux thermal probe TP02 (figure 10). Low heat flow (0.87 Wm$^{-1}$) has been used similar to the low experimental heat flow. Time (1500s) with time step 0.01 s. and 20 °C has been used as boundary conditions.
For glass beads the porosity was modelled for 10 mm diameter with Comsol Multiphysics® axisymmetric 2D to investigate the effect of porosity on the thermal conductivity (figure 11). Thermal conductivity for materials with modelling porosity was $0.12 \text{ W (mK)}^{-1}$ (close to experimental value) while without modelling porosity was $0.21 \text{ W (mK)}^{-1}$.

For insulation materials, Simulation curve has been modelled in COMSOL to validate the experimental test for glass wool (figure 12). The slight difference between the simulation and
experimental is attributed to the effect of the radiation inside glass wool materials, heat loss through the base of the thermal probe and to the accuracy of temperature. In any case the simulation with COMSOL is considered validate with the experimental test.

![Graph](image)

**Figure 12.** Validation the experimental test with simulation of COMSOL for glass wool.

5. **Conclusion**
Porosity and thermal conductivity of different porous materials have been investigated by Hukseflux® TP02 probe in the present study. Glycerol has been selected to calibrate the Hukseflux® TP02 probe due to absence of porosity. The variation of temperature with logarithm time is linear for Glycerol and thermal conductivity can be measured from the slop \( \frac{Q}{4\pi \lambda} \) of approximate equation directly. For porous materials, porosity plays an important role in thermal properties of these materials.

Porosity of glass beads have been measured by saturation method and the experimental results show that the porosity increases with diameter of glass beads. The porosity of glass wool and rock wool have been calculated by Helium pycnometer (Accupyc 1330) and flow resistivity method respectively. Thermal conductivity of porous materials (glass beads and insulation materials) has been calculated by Hukseflux® TP02 thermal probe. The experimental results show that thermal conductivity decreased with porosity.

Comsol Multiphysics® software has been used to validate the experimental tests. All boundary conditions of the experimental have been modelled in axisymmetric 2D Comsol Multiphysics® to get a match between simulation and experimental. However, using of Comsol Multiphysics® is useful and important to validate the experimental test of Hukseflux® TP02 thermal probe.

6. **References**
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