International Journal of Engineering & Technology, 7 (4.20) (2018) 536-540

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper



The Effect of Magnitude and Direction of Heat Flow on the Thermal Conductivity for Insulation Materials (Glass Wool) by Using Probe Method

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Abstract

The thermal energy of building is determined by the thermal properties of the materials and how to install these materials in the elements of buildings according to the direction of heat transfer. The effectiveness of thermal insulation (glass wool) is dependent on its thermal conductivity which is varies in different directions of fibers of glass wool. Glass wool is formed of fibers and binders tangled together during the industrial process to provide some elasticity. The experimental values of thermal conductivity of the insulation materials are changed according to magnitude of the heat power and direction of fiber arrangement. The thermal conductivity for insulation materials has been measured by using probe method, Huekseflux ® TP02 used to measure the thermal conductivity by emit the flow perpendicular and parallel to the fibers of glass wool. Two samples of yellow glass wool (density 68 kg/m3) with dimensions (10 ×10 ×30) cm have been used. Hot Disk bulk isotropic module has been used to evaluate thermal conductivity. TPS source (Hot Disk probe reference: 4922) characterized by a diameter of 14.61 mm has been selected. COMSOL® multiphysics axisymmetric 2D model has been used to follow the axial and the radial directions of the heat transfer.

Keywords: *Flow; Glass wool; Insulation; probe method; Thermal conductivity.*

1. Introduction

The strands protection materials are frequently ordered to characteristic filaments (hemp, flax, cotton, jute ...) and modern strands, for example, (glass filaments and polymeric filaments). For high temperature application, now and again utilize the metal filaments (steel strands, alumina filaments and others strands) as protection [1]. Warmth transmit in a stringy material happen through conduction and radiation. The convection warm transmit can be disregarded because of the grinding between the interstitial liquid and filaments which is confine development convective inside stringy materials [2]. Anyway, the radiative warmth transmit winds up extraordinary criticalness in high-temperature applications [3] while conductive warmth transmit through sinewy materials happen in temperatures near standard temperature [2]. The conductive warmth transmit occur through the filaments and the interstitial liquid, at that point the conductivity these segments is impact on the viable warm conductivity for protection material [4].

The warmth is exchange amid the conduction through the filaments and the interstitial liquid (frequently air) in parallel or arrangement ways. Conductive warmth transmit is occur in parallel way if the stream of warmth amid material synchronous was in parallel way. The aggregate rate of warmth stream amid the medium is equivalent to the summation of the warm conductance of every way [5].

The impact of the power disseminated per unit length of the test is impact on the warm conductivity in light of the fact that the variety of the temperature expanded with high warmth control.The expression λ_{eff} in "(1)," is define the thermal conductivity for porous materials which is depends on the amount of thermal conductivity of interstitial fluid and fibers (often air) [5].

$$\lambda_{eff} = \emptyset . \lambda_f + (1 - \emptyset). \lambda_i \quad (1)$$

Where λ_{eff}, λ_f and λ_i are effective, fiber and interstitial fluid thermal conductivity of fibrous materials [W/m.K] respectively while $\emptyset$ is representing solid volume fraction.

The assumptions of this "(1)," above:

For the first term λ_{eff} is that the heat is flow as solid block while in fact the heat is flow during small fiber-to-fiber contact. On the other hand for the second term, the interstitial fluid (often air) does connect to the source of heat, especially for fibrous materials.

All the porous insulation materials have low solid volume fractions due to the high porosity for this materials "(2),".

$$\emptyset = (1 - \varepsilon) \quad (2)$$

Where ε is representing total porosity.

Van der Held in 1952 [6], [7] notes that the radiation occur easily in high porosity materials. He observed that high temperature gradients occur at the probe surface when high probe powers are used in insulation materials, so increasing the radiation effect.

Woodside in 1958 [8], notes that there is extrusive variation between the heat power and thermal conductivity. He measured thermal conductivity for dry silica aerogel with different power.

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(Table 1) shown increasing heat power tend to increase thermal conductivity for dry silica aerogel.

Table 1: Increasing heat power with thermal conductivity for dry silica aerogel [8]

Input power (W/m)	Specimen temperature (°C)	Apparent thermal conductivity (W/m .K)
0.012	21.4	0.0238
0.021	21.7	0.0243
0.046	22.3	0.0266
0.096	23.4	0.0268
0.17	25.2	0.0274

Eschner et al in 1974 [9], was noted that rising temperature comes from increased power input gives results of high thermal conductivity.

The results of Davis and Downs in 1980 [10] on the phenolic foam show that increasing heat power gave as high thermal conductivity values. The same results was obtained by Pilkington in 2008 when he used the same materials (phenolic foam) where the results are higher for the higher power input.

2. Thermal probe method (Hot Wire) technique

The probe method for determination of thermal conductivity depends on assumptions that long line of heat source is infinitely and inserted in homogeneous materials. It is defined by the general equation of Fourier "(3),":

$$\frac{dT}{dx} = \alpha \nabla^2 T \tag{3}$$

For initial condition: at $t \leq 0$, $\Delta T(r, t) = 0$
With condition:

at r= 0 and $t \geq 0$, $\lim_{r\to 0}\left[\frac{rdT}{dr}\right] = -\frac{Q}{2\pi\lambda}$ (4)

at r = ∞ and $t \geq 0$, $\lim_{r\to\infty}[\Delta T(r,t)] = 0$ (5)

The solution of Carslaw and Jaeger [11] depends on consideration the heat source over time at a constant rate:

$$\Delta T = -\frac{Q}{4\pi\lambda} Ei\left[\frac{-r^2}{4\alpha t}\right] \tag{6}$$

Where ΔT, Q, r, α and t representing temperature [K], linear electrical power [W/m], distance from the heat source [m], thermal diffusivity, [m^2/s] and time [s] respectively.

Where:

$$u = \frac{r^2}{4\alpha t} \tag{7}$$

By using a series expansion [12], the exponential function (E_i) can be expressed:

$$-E_i(-u) = \int_u^{\infty}\left[\frac{e^{-u}}{u}\right] du \tag{8}$$

Where:

$$-E_i(-u) = -\gamma - ln(u) - \frac{(u^2)}{2.2!} + \frac{(u^3)}{2.3!} - \tag{9}$$

And γ representing Euler's constant (0.5772157…).

Equation (9) will represent by using Euler's constant [γ].

Carslaw and Jaeger [11] solved "(1)," after consideration no change in thermal properties of the probe and heat flow (Q) is constant.

$$\Delta T = -\frac{Q}{4\pi\lambda}\left[-\gamma - ln(u) - \frac{(u^2)}{2.2!} + \frac{(u^3)}{2.3!} - \ldots\right] \tag{10}$$

For the long time (small u value), the values after logarithmic part can be neglected and the variation of temperature can be expresses by:

$$\Delta T = \frac{Q}{4\pi\lambda}\left[\left[ln\left(\frac{t_2}{t_1}\right)\right] + B\right] \tag{11}$$

Where:

$$B = ln\left\{\frac{4\alpha}{r^2}\right\} - \gamma + \frac{2\lambda}{rH} \tag{12}$$

The second part (B) in "(11)," used to find the thermal diffusivity if the value of H (conductance) of the represent air gap between probe and materials . The value of H , [W/m^2.K] varies highly according to the contact between the probe and surrounding material [13].

The variation of ΔT against ln (t) becomes linear with slop equal to $\frac{Q}{4\pi\lambda}$, then the thermal conductivity can be obtained from:

$$\lambda = \frac{Q}{4\pi}\left[\frac{ln(t_2/t_1)}{T(t_2)-T(t_1)}\right] \tag{13}$$

The term (Q/4πλ) in "(13)," is representing the slope and used to determine thermal conductivity.

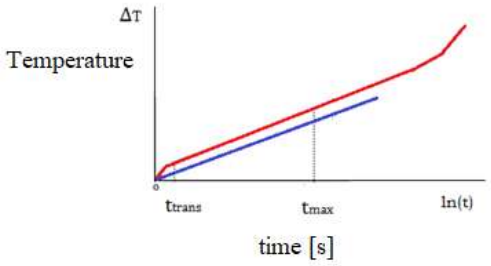


Fig. 1: Variation of temperature against natural logarithm

For porous materials (such as insulation materials) when the porosity increased (figure 2 for glass wool) the variation of temperature with the logarithm of the time is non-linear so we must choose the value of t_1 and t_2 to find thermal conductivity.

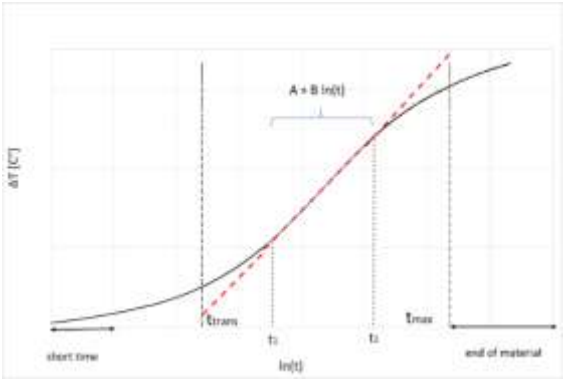


Fig. 2: Variation of temperature against natural logarithm of the time for glass wool

At short time (< t_{trans}): Vos [14] defined this period by:

$$t_{trans} = \frac{50.(R_s)^2}{4.\alpha} \tag{14}$$

At long time (> t_{max}): the nonlinearity curve attributed to the axial heat losses at the end of the probe and heat exchange with ambient atmosphere (when the heat reaches the external limits of the material). Vos [14] was determined the time t_{max} by:

$$t_{max} = \frac{0.6\,(r-R_s)^2}{4.\alpha} \quad (15)$$

Figure 2 represents temperature variation versus natural logarithm of the time for porous materials (glass wool). During the experimental, to apply the "(13)," and to achieve the ASTM recommendation [15] approximate values between t_1 and t_2 where there is a linear was chosen to find thermal conductivity.

3. Experimental with thermal probe

The experimental was done with Hukseflux® probe (TP02) (figure 3). The base of the probe TP02 contain reference temperature sensor (Pt_{1000}) (thermocouple 1). Hukseflux TP02® probe has two thermocouple, cold joint in the end of the of needle (thermocouple 4) and hot joint at 1/3 of needle length (thermocouple 3).

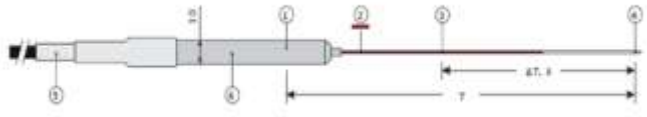


Fig. 3: TP02 Hukseflux® probe

Metal of constantan has been chosen for a hot wire heater because this metal has high electrical resistivity and low temperature coefficient. The outer face of the Probe made of stainless steel due to its low thermal diffusivity (Table 1).

Table 2: Thermal properties of the probe layers.

Details of layers	Thickness [mm]	Thermal conductivity [W/(m.K)]	Density [kg/m3]	Specific heat [J/(kg.K)]
Hot wire (Constantan)	0.065	19.50	8910	390
Insulant (Glass pearl)	0.355	0.16	1600	800
Outer face (Steel)	0.330	16.00	7900	500

Variation of temperature ΔT, between the cold and the hot joint is recorded and measured by the main sensor signal:
signal:

$$\Delta T = \frac{U_{sen}}{E_{sen}} \quad (16)$$

The reference temperature sensor (Pt_{1000}) is used to correct the base temperature:

$$E_{sen} = (39.40 + 0.05\ T - 0.0003\ T^2) \quad (17)$$

The TPSYS02 control interface supplying (figure 4) constant heat power during the duration of the test. Three heat power levels are supplying by TPSYS02; low heat flow of 0.87 $W.m^{-1}$, medium heat flow of 2.64 $W.m^{-1}$ and high heat flow of 4.44 $W.m^{-1.}$



Fig. 4: Image of probe TP02 Hukseflux ® and the TPSYS02

3.1 Effect magnitude of heat power

Thermal conductivity for insulation materials (glass wool chosen) has been selected to study effect of the heat power supply with TP02. Temperature variation at the external surface of the probe must be less than 1°C according to the Hukseflux probe to minimize effect of heat transfer during radiation phase inside fibrous materials especially. This condition is not valid in TP02 because the variation of temperature is 13 °C for low flow, 37 °C for medium flow and 63 °C for the high flow power supply according to the heat power supply by TP02 (high 4.44 W/m, medium 2.64 W/m and low 0.87 W/m).
Figure (5) illustrates that the variation of temperature during the experimental test for glass wool is more than 1 °C. the condition of temperature increase less 1°C was achieved just in modelling of Comsol Multiphysics®.

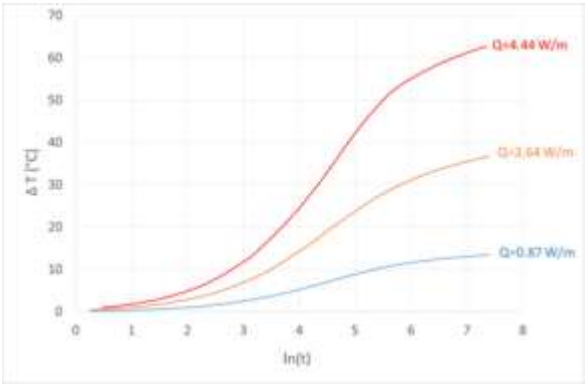


Fig. 5: Variation of temperature for different heat power

The value of thermal conductivity that has been calculated from experimental was 0.033 W/m.K for low heat flow supply and 0.038 W/m.K for high heat flow supply [16]. Our experimental results were closed to the results of Woodside in [8], Eschner et al [9], R. Coquard [17] and Pilkington [18].

3.2. Effect of direction of the heat power

Effect the direction of the flow inside the fibrous insulation materials has investigated with TP02. Two samples dimensions (10 ×10 ×30) cm with density (68 kg/m3) have been cut in different direction to evaluate effect the direction (figure 5). The selection of sample it was chosen according to the fibrous structure.

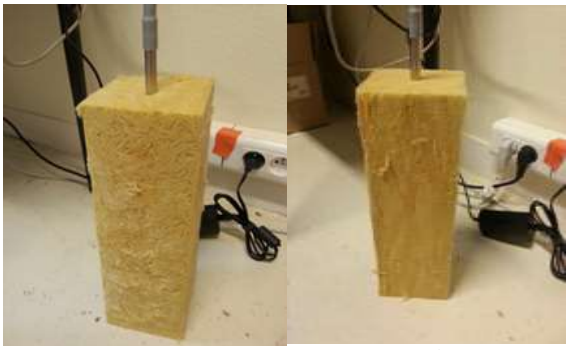


Fig. 6: Parallel and Perpendicular heat flow

The low flow (0.87 W/m) with time (1500s) was selected to study effect of direction of heat flow.

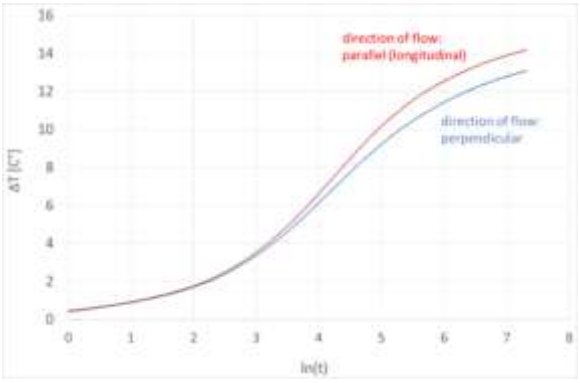


Fig.7: Variation of the thermal conductivity according to the direction of flow

3.3. COMSOL Multiphysics® simulation

COMSOL Multiphysics® software has been selected and axisymmetric 2-D a plane module has been used . This software was selected to study the influence heat power during variation of temperature (figure 8).

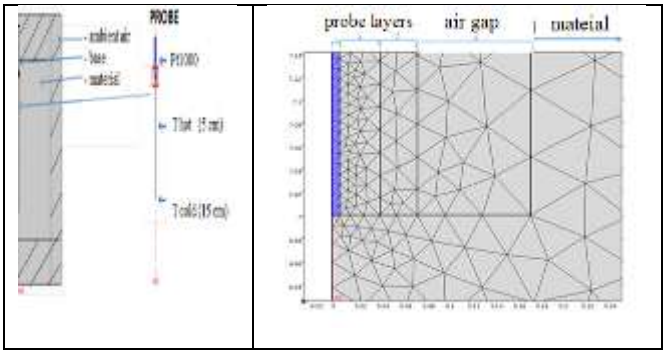


Fig.8: Axis-symmetry probe and automatic mesh in COMSOL

The same experimental heat flux power (0.87 W/m) and maximum time (1500 s) permitted by the control interface was chosen. Time step 0.01 s with ambient air of 20 °C was defined as the boundary conditions. COMSOL is to reduce the computational time and power besides studying the influence of parameters that cannot be accessible experimentally (figure 9).

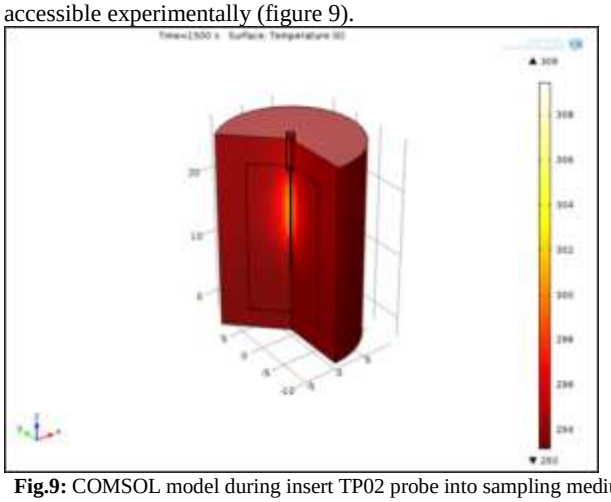


Fig.9: COMSOL model during insert TP02 probe into sampling medium

we note in figure 10, the low flow reduce the S-shaped for variation temperature against natural logarithm. The result of thermal conductivity 0.0347 W/(m.K) has been obtained and it's consistent with the value 0.035 W/(m.K) cited in the references.

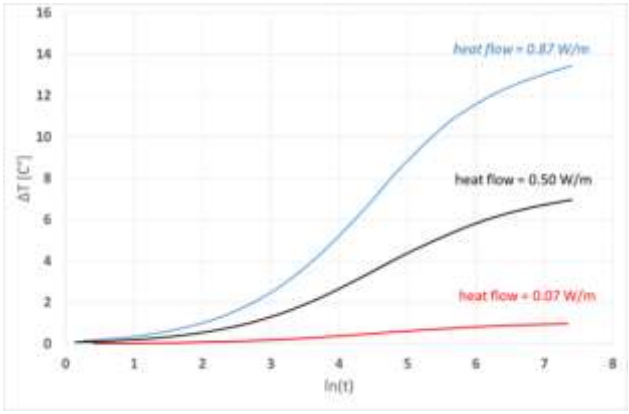


Fig. 10: Results heat flow on glass wool with COMSOL

4. Isotropic measurement in different direction with TPS

Hot Disk (TPS 2500) and bulk isotropic module have been used to determine thermal conductivity. Probe reference: 4922 with diameter of 14.61 mm has been selected.
In order to produce a large range of viable data points and a large temperature gradient to ensure the accuracy of the measurement, output power and measuring time have been selected 40 mW and 160s respectively to respect the International Standard ISO 22007-2 recommended 0.1 W. We have chosen to reduce this flow to 40 mW in order to obtain an increased temperature near 1°C (exact value obtained is 0.46°C) which is well adapted for insulation materials (figure 11).

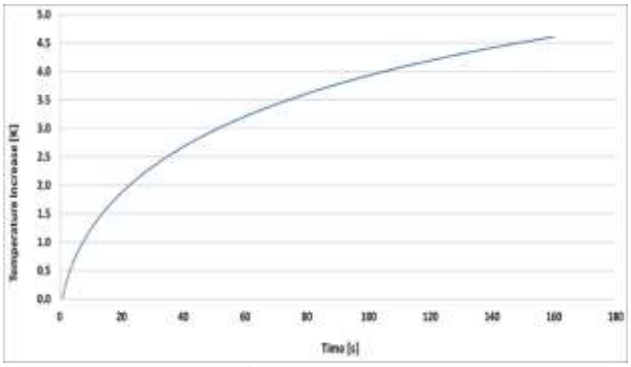


Fig.11: Transient curve for the isotropic experimental measurement

Semi-infinite assumption has been respected by obtained characteristic time of 0.353 s and a probing depth of 17.4 mm.
Tests are carried out for sample of dimensions (10×10×10) mm at temperature (20 °C) in three directions (X, Y and Z) to evaluate thermal conductivity (figure 12). Three planes of fibers have been studies to satisfy different structures of the glass wool in each direction.

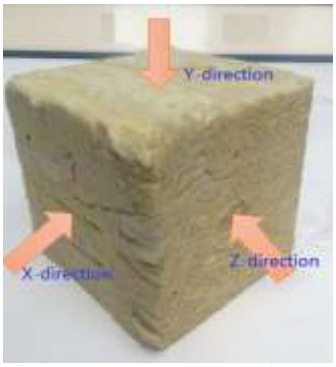


Fig. 12: X, Y and Z-directions of the flow

TPS probe sensor has been inserted in directions X, Y and Z. During first case (X and Y directions), probe is inserted perpendicular of the stratification plane of fibers while in the second case (Z-direction) probe is parallel. Experimental values in the direction X and Y are closed together while value in the Z-direction are bigger than the other ones (Table 1). Probe can be inserted in the 3 directions themselves (Table 3). Values in the Z-direction are bigger than the other ones. In the first case (X and Y directions), probe is inserted perpendicular of the stratification plane of fibers instead of in the second case (Z-direction) probe is parallel.

Table 3: Thermal conductivity with different directions.

Direction	X-direction	Y-direction	Z-direction
Thermal Conductivity	λ_X=0.03807 [w/m.k]	λ_Y=0.03914 [w/m.k]	λ_Z=0.04098 [w/m.k]

5. Conclusion

Different successful experimental tests were done to study effect of heat power and its direction on thermal conductivity. Non-Steady-State Probe (Hukseflux® TP02) Needle length 150 mm and diameter 1.5 mm has been used. Long standing relation of approximation is used to specify thermal conductivity by using TP02 probe. The study showed that decrease heat power tend to reduce variation of temperature and therefore reduce thermal conductivity. Reducing heat power makes thermal conductivity values more accurate in comparison with reference values.

The effect of the heat flow direction was investigated with using Hukseflux® TP02. The experimental results showed that the thermal conductivity during insert the probe perpendicular to the fibers is more than the thermal conductivity during insert the probe parallel to the fibers because in the first case the heat flow becomes in the longitudinal direction of the fibers.

COMSOL Multiphysics® with axisymmetric module 2-D used to reduce heat flux less than (<0.1 W/m) and to provide a good accuracy for thermal conductivity and less than (<0.07 W/m) makes temperature increase less than 1°C. Requirements of control interface connected with Hukseflux probe cannot be fulfilled the previous conditions.

TPS sensor was also used to calculate the thermal conductivities in the directions X, Y and Z inside the glass wool materials and the results showed that the thermal conductivity is changed according to the distribution of fibers inside the structure of the material.

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