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Total Thermal Diffusivity in a Porous Structure Measured By Full Field Liquid Crystal Thermography

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Abstract –We propose a measurement technique for the investigation of the total thermal diffusivity in a streamed porous structure. It is based on measuring the full 2D temperature field using a thermochromic liquid crystal foil. By a proper calibration of the colour play of such foils they can be used for accurately measuring the temperature. From the observed temperature field the total thermal diffusivity is estimated by an optimum search in a numerical simulation of the governing equation. It is observed that the lateral total thermal diffusivity is reproducibly measureable whereas the longitudinal contains large uncertainty. Comparing the lateral total thermal diffusivity to the effective thermal conductivity of our foam we found a good agreement. Distinguishing between the contribution of heat transfer through the solid and heat transferred by the fluid has not been possible due to larger measurement uncertainty at low flowrates.

Keywords**:** Porous media, Thermal diffusivity, Effective thermal conductivity, Thermochromic liquid crystal.

1. Introduction

There is the trend in the chemical and pharmaceutical industry to go from batch to continuous reactors. In the case of heterogeneously catalysed reactions a promising approach is to use porous foam structures as catalyst support. Apart from a high specific surface area such foam structures provide a good thermal conductivity. This is important to even out the temperature over the reactor domain. In this work we present a method to quantitatively measure the total thermal diffusivity in a streamed porous structure. In contrast to previous works that measured the temperature point-wise by thermocouples our approach is to measure the full 2-D temperature field using a thermochromic liquid crystal (TLC) foil. TLC foils show a gradual colour change from red to green and blue with increasing temperature. The colour change is repeatable and irreversibility is only observed when the temperature is much higher than the colour play range (Anderson and Baughn, 2004). With an appropriate calibration the uncertainty can be as low as 1% of the colorplay range (Wiberg and Lior, 2004). For the calibration the recorded image which is usually in RGB (red-green-blue) color space is transformed to the HSV (hue-saturation-value) colour space. In this representation the hue value uniquely relates to a temperature. In our case a point-wise calibration of the entire test surface was employed like done by Sabatino et al. (2000). Like this the uncertainty stemming from foil non-uniformity, viewing angle and lighting angle are treated by the calibration.

2. Experimental

We investigated aluminium foam from ERG Aerospace Corp. It has dimensions of 280x200x15mm and a pore size of 40ppi (pores per inch). The porosity of this foam is 88.6%. The measurement idea is to build a setup in which a 2-D temperature field evolves. The principal scheme is shown in Figure 1 (left). It shows cold air entering from the right and streaming through a porous structure. At two sides of this porous structure hot aluminium profiles provide heat. To ensure two-dimensionality the setup is insulated in the third dimension. Figure 1 (right) shows the entire setup including the two plexiglass plates on top and bottom and the two isolations made of cellular plastic.

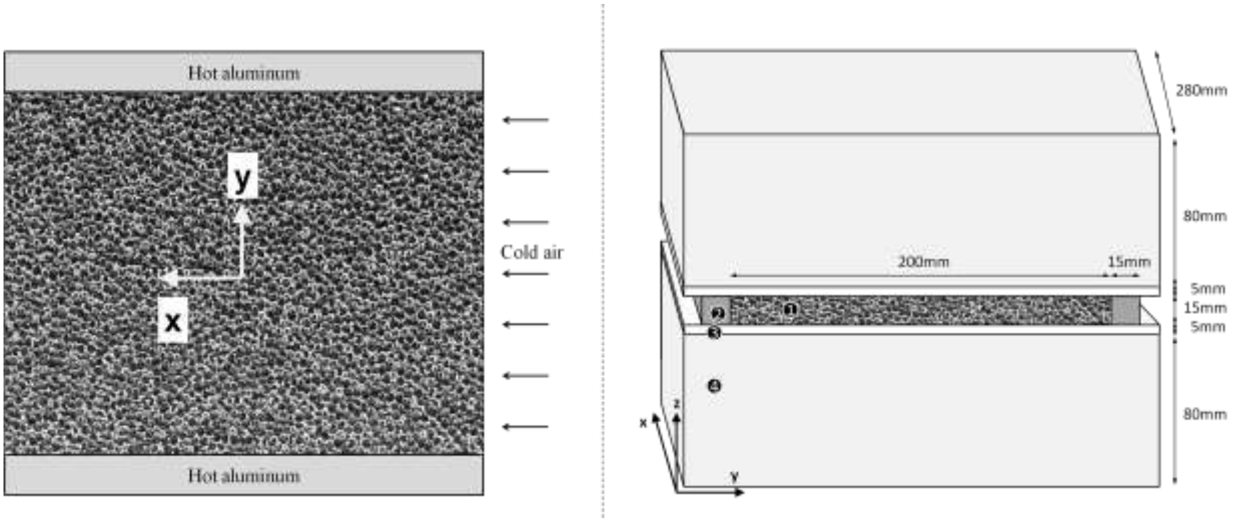

Fig. 1. Left: Porous structure streamed by cold air. Right: Illustration of setup showing the porous structure (1), the tempered aluminium profiles (2), plexiglass plates on top and bottom (3) and a cellular plastic insulation both on top and on the bottom of the setup (4). The TLC foil is placed between the porous structure and the upper plexiglass plate.

The liquid crystal foil for measurement of the temperature is placed between the porous structure and the upper plexiglass plate. For the measurement the upper cellular plastic was removed shortly before a picture was taken. It was found that the time between the removal of the insulation and the recording of the picture was shorter than the time scale required for changes in temperature. We used a standard digital camera (Canon Digital IXUS 700) with integrated flash for illumination. The whole setup was isolated from other light sources. This is crucial because the colour of the TLC foil depends on the colour of the incident light and on its angle.

A critical issue in the design of this experiment is the two-dimensionality. This should be discussed in the following. In the conservation equation introduced below we will assume that there are no gradients in the z-direction. We will justify this assumption by calculating the heat flux in z-direction and comparing it to the total heat flux. In the experiments the air inlet temperature is 23°C and the temperature of the heated wall is 33°C. If the fluid would reach the temperature of the wall this would correspond to 54W transferred to the fluid. This number has to be compared to the heat that could be transferred in z-direction. The heat transfer coefficient through the plexiglass (0.19W/mK) and the cellular plastic (0.04W/mK) in series is as small as $0.5\mathrm{W/m^2K}$. Assuming a temperature difference of 10°C the heat loss is only 0.55W. In other words the heat transferred through the top and bottom of the setup amounts to only 1% of the heat transferred in total. It seems therefore reasonable to assume that a two dimensional temperature profile evolves.

3. Theory

We assume constant thermophysical properties of the air. This is justified by the fact that the temperature variations are very small, i.e. less than 10°C. The interstitial flow velocity u is therefore homogeneous in the whole setup. Further assuming local thermal equilibrium between the solid and the fluid a single conservation equation can be used (Kaviany, p.215):

$$\left[\varepsilon \cdot \left(\rho\, c_p\right)_f + (1-\varepsilon) \cdot \left(\rho\, c_p\right)_s\right] \cdot \frac{\partial T}{\partial t} + \left(\rho\, c_p\right)_f \cdot u \cdot \frac{\partial T}{\partial x} = \left(\rho\, c_p\right)_f \cdot D_{\parallel} \cdot \frac{\partial^2 T}{\partial x^2} + \left(\rho\, c_p\right)_f \cdot D_{\perp} \cdot \frac{\partial^2 T}{\partial y^2} \qquad (1)$$

Here ε is the porosity and f and s labels the fluid and the solid. The two transport terms in longitudinal and lateral direction are introduced below. As all our measurements are done in steady-state, the time derivatives vanish:

$$u \cdot \frac{\partial T}{\partial x} = D_{\|} \cdot \frac{\partial^2 T}{\partial x^2} + D_{\perp} \cdot \frac{\partial^2 T}{\partial y^2} \qquad (2)$$

This equation contains two parameters. The total thermal diffusivity in longitudinal direction:

$$D_{\|} = \frac{k_{eff}}{(\rho\, c_p)_f} + D_{\|}^{d} \qquad (3)$$

is composed of the effective thermal conductivity k_{eff} and of the thermal dispersion in longitudinal direction. Similarly the total thermal diffusivity in lateral direction:

$$D_{\perp} = \frac{k_{eff}}{(\rho\, c_p)_f} + D_{\perp}^{d} \qquad (4)$$

is composed of the effective thermal conductivity and the thermal dispersion in lateral direction. The effective thermal conductivity of our foam was assumed isotropic. Nevertheless the contribution of the dispersion term leads to an anisotropic total thermal diffusivity.

4. Results and Discussion

First some explanations about the evaluation of the experiment should be given. The measurement domain is sub-divided into square areas in which a homogeneous temperature is assumed. We divided our experimental domain into squares of 5.7mm. The temperature field is therefore subdivided into 35x49 values. Equation 2 is then discretized using a central finite difference scheme. This allows to simulate the temperature field and compare the simulation to the measurement. As boundary condition for the simulation we took the measured temperatures at the boundary of the domain. In an optimum search the two unknown thermal diffusivities are then estimated such that the root mean square difference between measured and simulated temperature is minimum. Figure 4 shows a comparison between a simulated (top) and measured (bottom) temperature field.

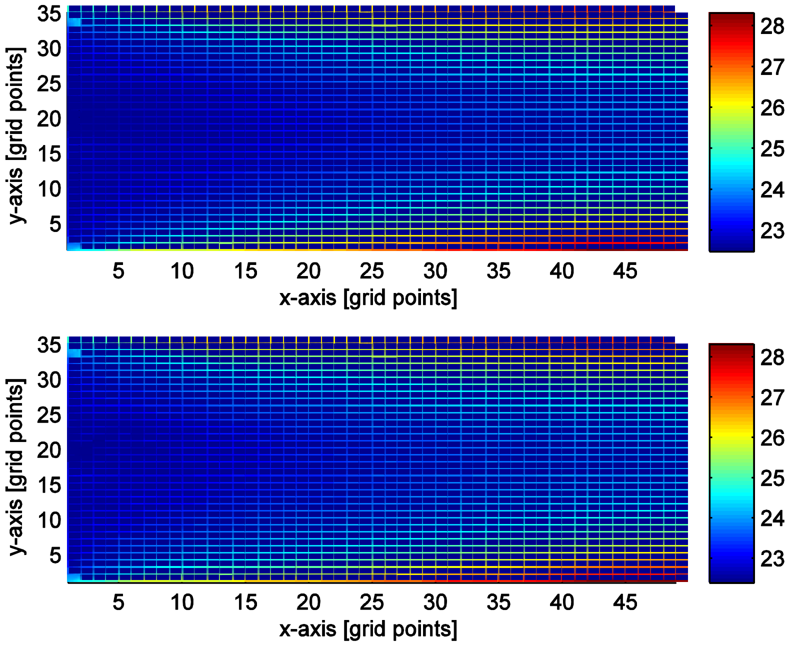

Fig. 4. Simulated (top) and measured (bottom) temperature profiles in comparison. The cold fluid streams from left to right.

We observed a good reproducibility of the lateral total thermal diffusivity. The longitudinal total thermal diffusivity appears however random. The reason is that the second derivative in streamwise direction is around zero, i.e. the temperature profile is almost linear (Figure 5 left). On the other hand the profile of the temperature in lateral direction shows a large positive second derivative (Figure 5 right).

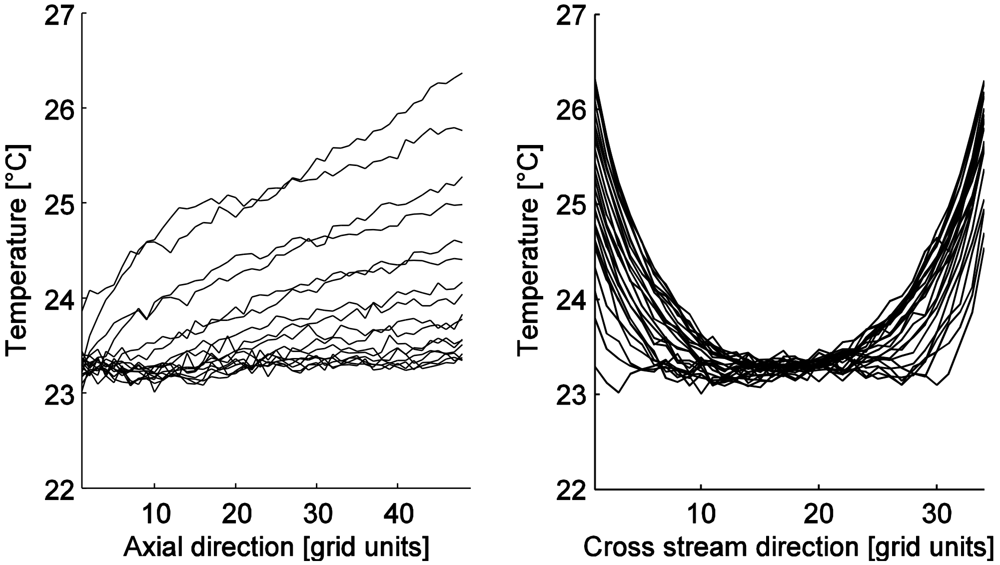

Fig. 5. Temperature profile in longitudinal direction (left) and lateral direction (right). It is observed that in longitudinal direction the temperature profile is almost linear, i.e. the second derivative is around zero.

Looking at equation 2 it becomes clear that if $\frac{\partial^2 T}{\partial x^2} \approx 0$ the parameter $D_{||}$ can take arbitrary values and the equation is still fulfilled. The consequence of this on the evaluation procedure can be investigated by setting $D_{||}$ to an arbitrary constant value. The optimum search is then made only for $D_{\perp}$. It was observed that for values of $D_{||}$ between 0 and 10 times $D_{\perp}$ the resulting $D_{\perp}$ does only change by 2%. This means that $D_{\perp}$ can still be measured irrespective of the value of $D_{||}$. For the following evaluations we decided to assume $D_{||} = D_{\perp}$ as through the effective thermal conductivity they are expected to have similar values.

Figure 6 shows the resulting lateral total thermal diffusivity as a function of the pore Reynolds number for experiments where the air is heated (x) and cooled (o). It is observed that the diffusivity is higher in the experiments where the fluid is cooled. Comparing the temperature profiles this means that in the cooling experiments the temperature profiles in the lateral direction is flatter. The flatter temperature profile can have several reasons. One is certainly the heat lost/gained in z-direction. This effect is more dominant at low flowrates. There the deviation is also most significant. At high flowrates however there is even an overlap of the results from heating and cooling. We therefore state that there is only a minor systematic difference between heating and cooling.

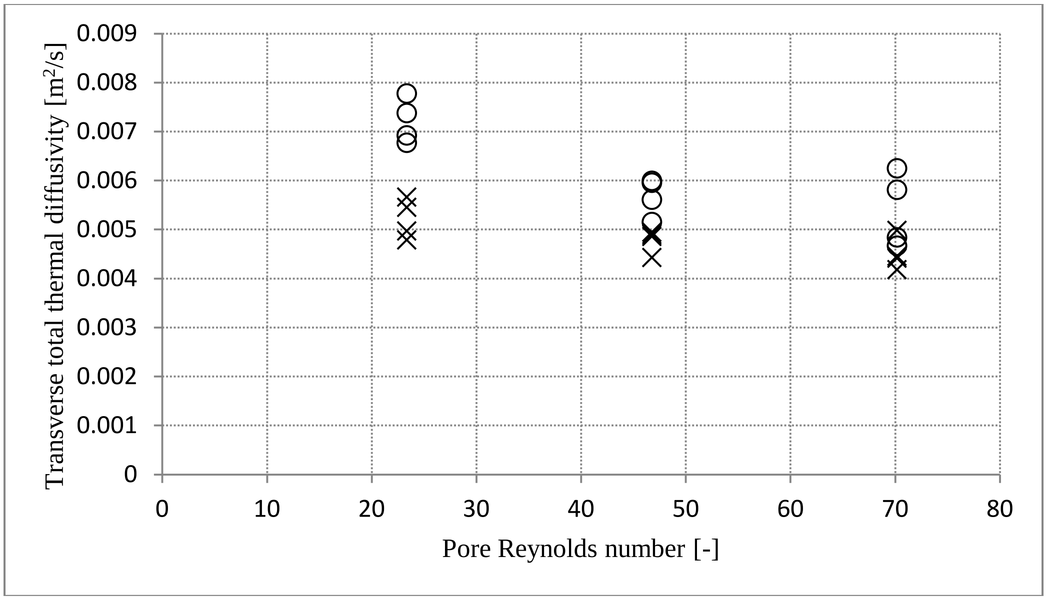

Fig. 6. Total thermal diffusivity in lateral direction as a function of pore Reynolds number. In one case the air was heated sideways (x) and in the other it was cooled (o).

It is observed that the diffusivity decreases with increasing flowrate. According to equation 4 the lateral total thermal diffusivity is composed of two components. The first is the effective thermal conductivity. It is a material constant of the solid and is a function of the material conductivity and the geometry of the porous foam. The second is the dispersion term that depends on the fluid flow and could therefore be dependent on the Reynolds number. Generally we would expect an increasing dispersion with increasing Reynolds number (Han et al., 1985). In our experiments however the values decrease with flowrate. The observed trend therefore has to be attributed to measurement uncertainty and it is not possible to distinguish between the contributions of heat transfer by the solid and the fluid.

We further compare the measured diffusivity to the effective thermal conductivity expected from models. There are various formulas to estimate the effective thermal conductivity of a porous structure from the bulk thermal conductivity of the material and its geometrical characteristics (Petrasch et al., 2008). For our foam structure the effective thermal conductivity can be estimated from the bulk thermal conductivity and the porosity according to a simplified equation proposed by the manufacturer (Web-1):

$$\mathrm{k_{eff}} = \lambda_{\mathrm{bulk}} \cdot (1-\varepsilon) \cdot 0.33 = 8.85\,\frac{\mathrm{W}}{\mathrm{mK}} \tag{5}$$

$$\frac{\mathrm{k_{eff}}}{(\rho\,\mathrm{c_p})_\mathrm{f}} = 0.00735\,\frac{\mathrm{m^2}}{\mathrm{s}} \tag{6}$$

Compared to this simple estimation our measurements show slightly lower values. It is difficult to say which is more valid but the close agreement of the values suggests that our measurement technique is reliable.

5. Conclusion

An experimental method was developed for the measurement of the full 2D temperature field in a streamed porous structure. From that the total thermal diffusivity in lateral direction was estimated. The resulting values agree well with the expected effective thermal conductivity. Distinguishing between heat transferred by the solid from heat transferred by the fluid was however not possible due to measurement uncertainty when the fluid flowrate is changed.

Acknowledgements

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