[3] leads to

$$\mathbf{q}_{\mathrm{vdif}} = -\frac{P}{RT} Df \frac{M_a M_v}{M_g} \left[\nabla \frac{p_{vs}}{P} + \frac{M_a - M_v}{M_a M_v} (M_a \omega_{vs} + M_v \omega_a) \frac{\nabla P}{P} \right]. \quad (6)$$

Here the second term within brackets has the opposite sign of $p_{vs}\nabla(1/P)$ and is of the same order of magnitude. This term is missing in ref. [3]. For $P = 1$ atm the expression in brackets is zero for $p_{vs}/P = 0.54$, corresponding with a temperature of 83.6°C. It is positive for lower values of p_{vs}/P.

If the authors agree with my point of view, the analysis of the pressure influence in ref. [3] should be revised.

Note added in proof—Dr Moyne has pointed out to me that in the pressure term of equation (5) a factor $\omega_1\omega_2$ is missing. This reduces the corresponding term in equation (6) by a factor of 4 or more. Hence, this term will be negligible in comparison with $p_{vs}\nabla P^{-1}$ in most cases.

Dan A. de Vries
Braakweg 21
5708 JJ Helmond
The Netherlands

REFERENCES

1. S. Azizi, C. Moyne et A. Degiovanni, Approche expérimentale et théorique de la conductivité thermique des milieux poreux humides—I. Expérimentation, *Int. J. Heat Mass Transfer* **31**, 2305–2317 (1988).
2. C. Moyne, J. C. Batsale et A. Degiovanni, Approche expérimentale et théorique de la conductivité thermique des milieux poreux humides—II. Théorie, *Int. J. Heat Mass Transfer* **31**, 2319–2330 (1988).
3. A. Degiovanni et C. Moyne, Conductivité thermique de matériaux poreux humides: évaluation théorique et possibilité de mesure, *Int. J. Heat Mass Transfer* **30**, 2225–2245 (1987).
4. D. A. de Vries, The theory of heat and moisture transfer in porous media revisited, *Int. J. Heat Mass Transfer* **30**, 1343–1350 (1987).
5. J. R. Philip and D. A. de Vries, Moisture movement in porous materials under tempeature gradients, *Trans. Am. Geophys. Un.* **38**, 222–232 (1957).
6. D. A. de Vries, Simultaneous transfer of heat and moisture in porous media, *Trans. Am. Geophys. Un.* **39**, 909–916 (1958).
7. D. A. de Vries, Het warmtegeleidingsvermogen van grond, Med. Landbouwhogeschool, Wageningen, pp. 1–73 (1952).
8. D. A. de Vries, The thermal conductivity of granular materials, Annexe 1952-1, Bul. Inst. Int. du Froid, pp. 115–131 (1952).
9. D. A. de Vries, Thermal properties of soils. In *Physics of Plant Environment* (Edited by W. R. van Wijk), Chap. 7. North-Holland, Amsterdam (1963).

Reply to 'Discussion of "Approche expérimentale et théorique de la conductivité thermique des milieux poreux humides"'

In reply to the discussion of our articles [1–3] by Prof. de Vries, we want to bring the foregoing comments following the order of his remarks.

1. *Method of de Vries or not*

De Vries' analysis in his pioneering work in 1958 [4] suggested a tentative formulation to express the apparent thermal conductivity of a wet porous medium (which is k in our notation) in the form (see equations (10) and (16) in ref. [4] or equations (5) and (9) in ref. [5] with the definition of the thermal vapour diffusivity D_{Tv})

$$k = \lambda' + f_{\mathrm{de\,Vries}} \zeta \lambda_{\mathrm{dif}} \quad (1)$$

where λ' is 'the thermal conductivity of the porous medium in the hypothetical case where no moisture movement occurs', 'excluding vapour movement'; $f_{\mathrm{de\,Vries}}$ is a factor which appears due to the section reduction for effective transfer (including the hypothetical transport through isolated islands); ζ is the ratio between the intrinsic gas phase average temperature gradient and the volume-averaged temperature gradient; and λ_{dif} is the apparent thermal conductivity of the pores due to the contribution of the vapour diffusion.

In our article [1], we proposed to use this tentative formulation in order to analyse our own experimental results by determining a so-called 'de Vries' experimental factor' f_{exp} by writing

$$f_{\mathrm{exp}} = f_{\mathrm{de\,Vries}} \zeta \quad (2)$$

and by identifying λ' with the thermal conductivity λ_0 measured at low temperature ($T \leqslant 20°\mathrm{C}$) where the evaporation–condensation effects seem to be experimentally negligible. Thus

$$k = \lambda_0 + f_{\mathrm{exp}} \lambda_{\mathrm{dif}}. \quad (3)$$

We called this factor 'de Vries' experimental factor' because we determined it experimentally following the conjecture of de Vries (in this view, the second line of Section 4.4 of ref. [1] should have read "la conjecture de de Vries conduit à" rather than "de Vries propose de").

Nevertheless we are pleased to accept the authorship of this method which gives a simple and efficient methodology to reach the apparent thermal conductivity k of a moist porous medium as a function of temperature and moisture content.

2. *Comparison between de Vries' work and our work*

With the notation of ref. [2], we express the vapour mass flux through the porous medium by analogy with Fick's law in the form

$$(\mathbf{n}_v)_i = -\rho_g \mathscr{D} f_{ij} \frac{\partial \langle \omega_v \rangle^g}{\partial x_j}. \quad (4)$$

where f_{ij} is the resistance factor to gaseous diffusion through the porous medium. The physical significance of the tensor f_{ij} is made clear by noting that f_{ij} is the tensor unity in the case of an homogeneous gas phase.

In his discussion de Vries argues that, neglecting the transport through liquid islands, we have in the 'wet walls' case

$$f = \varepsilon_g \zeta \quad (5)$$

which is the form that he proposed (without derivation) in his own papers [4, 6].

In fact we can derive this result beginning with equation (46) in ref. [2], noting that in the 'wet walls' case $\xi_g \equiv 0$ and applying the averaging theorem (knowing that $\langle \chi^g \rangle = 0$). Therefore, we have

$$f_{ij} = \varepsilon_g \left(\delta_{ij} + \left\langle \frac{\partial \chi_j^g}{\partial x_i} \right\rangle^g \right). \quad (6)$$

On the other hand, equation (33) yields

$$T_g = \langle T \rangle + \chi_j^g \frac{\partial \langle T \rangle}{\partial x_j}. \tag{7}$$

As χ^g varies significantly over the length of the pores whereas $\langle T \rangle$ varies over the macroscopic length of the pores, we obtain

$$\frac{\partial T_g}{\partial x_i} = \frac{\partial \langle T \rangle}{\partial x_i} + \frac{\partial \chi_j^g}{\partial x_i} \frac{\partial \langle T \rangle}{\partial x_j} \tag{8}$$

and then

$$\left\langle \frac{\partial T_g}{\partial x_i} \right\rangle^g = \left(\delta_{ij} + \left\langle \frac{\partial \chi_j^g}{\partial x_i} \right\rangle^g \right) \frac{\partial \langle T \rangle}{\partial x_j} \tag{9}$$

which was to be demonstrated. It is interesting to note that the imposed liquid–vapour equilibrium at the gas interfaces causes the tortuosity and the constriction effects to disappear.

So we agree with de Vries' conclusions: in the 'wet walls' case, we have to identify k with λ^+ and f with $(\varepsilon_g \zeta)$.

3. *Influence of the pressure diffusion on the gaseous transport in porous media*

In our approach of the gaseous transport through porous media in ref. [3], we have only retained a convective term according to Darcy's law with a total pressure gradient as the driving force and a diffusive one according to a modified Fick's law. So we have always neglected minor effects such as thermal diffusion or pressure diffusion. Of course, the main effect due to a total pressure gradient is the convective terms of filtration (even if for mathematical correctness we have kept the derivatives relative to the three variables temperature, moisture content and total pressure in the expression of the diffusive term). Thus our analysis in ref. [3] does not need to be revised. Nevertheless de Vries' comment points out the interest of a much more sophisticated approach in the description of gaseous transport in porous media.

S. Azizi, C. Moyne, A. Degiovanni and J.-C. Batsale
Laboratoire d'Energétique et de Mécanique Théorique et Appliquée
Ecole des Mines
Parc de Saurupt
F54042 Nancy Cedex, France

REFERENCES

1. S. Azizi, C. Moyne et A. Degiovanni, Approche théorique et expérimentale de la conductivité thermique des milieux poreux humides—I. Expérimentation, *Int. J. Heat Mass Transfer* **31**, 2305–2317 (1988).
2. C. Moyne, J. C. Batsale et A. Degiovanni, Approche théorique et expérimentale de la conductivité thermique des milieux poreux humides—II. Théorie, *Int. J. Heat Mass Transfer* **31**, 2319–2330 (1988).
3. A. Degiovanni et C. Moyne, Conductivité thermique de matériaux poreux humides: évaluation théorique et possibilité de mesure, *Int. J. Heat Mass Transfer* **30**, 2225–2245 (1987).
4. D. A. de Vries, Simultaneous transfer of heat and moisture in porous media, *Trans. Am. Geophys. Un.* **39**, 909–916 (1958).
5. D. A. de Vries, The theory of heat and mass transfer revisited, *Int. J. Heat Mass Transfer* **30**, 1343–1350 (1987).
6. J. R. Philip and D. A. de Vries, Moisture movement in porous materials under temperature gradients, *Trans. Am. Geophys. Un.* **38**, 222–232 (1957).