The current issue and full text archive of this journal is available at
www.emeraldinsight.com/0961-5539.htm

Received 4 March 2009
Revised 10 May 2009
Accepted 15 May 2009

Energy flux vectors as a new tool for convection visualization

Kamel Hooman
School of Engineering, The University of Queensland, Brisbane, Australia

Abstract

Purpose – The aim of this paper is to introduce a new technique for convection visualization. This is similar to Bejan's heatlines and is even an exact match to Landau and Lifshitz's energy streamlines for two-dimensional geometries.

Design/methodology/approach – The work benefits from a combination of numerical and analytical tools to show that, in two-dimensional space, heatlines and energy streamlines are effectively the same. More importantly, the energy flux vectors are tracing both of them accurately; as verified for some cases of free and forced convection problems in this paper.

Findings – The new technique is easier to implement compared to the existing counterparts which are available in the literature. More specifically, the advantage of this new technique is that, contrary to heatlines and energy streamlines, it does not require further numerical analysis in addition to solving momentum and energy equations.

Originality/value – Energy flux vectors offer higher resolution compared to existing visualization tools.

Keywords Flow, Convection, Visual programming

Paper type Research paper

Introduction

According to Bejan (1984), it is crucial for the problem solver to have the chance to *see* the results of his solution so that he will learn from experience and thus improve his technique. This argument, put forward in 1983 by Kimura and Bejan (1983), led to the invention of *heatline* and *heatfunction* concepts. Bejan (1984) highlights the fact that in convection problems one should see the flow of fluid and, riding on this, the flow of energy. In what follows Bejan's heatline concept will be presented and applied to certain cases. Numerical procedure that should be undertaken to obtain the heatline distributions will also be discussed. Then, the application of *Energy Flux Vectors*, which is a new visualization technique, will be put forward. Based on this concept, one would still *see* the flow of energy without the need to solve a new set of numerical equations (that is generally required to obtain heatline distribution). Moreover, it will be shown that, applying the energy flux vectors the difficulty of formulating the appropriate boundary conditions for heatlines and energy streamlines can be overcome.

Heatline definition

For a two-dimensional incompressible flow streamfunction $\psi^*(x^*, y^*)$ satisfies the following mass continuity equation:

$$\frac{\partial u*}{\partial x*} + \frac{\partial v*}{\partial y*} = 0 \tag{1}$$

Provided that:

$$\frac{\partial \psi*}{\partial y*} = u* \qquad \frac{\partial \psi*}{\partial x*} = -v* \tag{2a,b}$$

International Journal of Numerical Methods for Heat & Fluid Flow
Vol. 20 No. 2, 2010
pp. 240-249

0961-5539
DOI 10.1108/09615531011016984

It is also known that the flow is locally parallel to the $\psi^* = constant$ line passing through a point. Therefore, one can simply follow the streamlines to *see* the real flow path.

When it comes to a convection problem, with thermal radiation being neglected, one remembers that the transport of energy through the flow field is a combination of convection and conduction. The heatfunction, $H^*(x^*, y^*)$, concept is defined by Kimura and Bejan (1983) in such a way that the net flow of energy (thermal diffusion and enthalpy flow) is zero across each $H^* = constant$ line. The difference between the values of two adjacent heatlines provides the magnitude of the energy flowing through the region bounded by the heatlines. Similar to the streamlines, heatlines also start and stop at boundaries or circulate as vortex throughout the flow region. The steady two-dimensional thermal energy equation for a fluid with constant density and specific heat is:

$$\rho c_p \left(u * \frac{\partial T*}{\partial x*} + v * \frac{\partial T*}{\partial y*} \right) = \frac{\partial}{\partial x*} \left(k \frac{\partial T*}{\partial x*} \right) + \frac{\partial}{\partial y*} \left(k \frac{\partial T*}{\partial y*} \right) \tag{3}$$

This equation can be rearranged, by taking the mass continuity equation into account, as:

$$\frac{\partial}{\partial x*} \left(\rho c_p u * T * - k \frac{\partial T*}{\partial x*} \right) + \frac{\partial}{\partial y*} \left(\rho c_p v * T * - k \frac{\partial T*}{\partial y*} \right) = 0 \tag{4}$$

Then, it is easy to define a function $H^*(x^*, y^*)$ to satisfy the above equation, in a very general form, as:

$$\frac{\partial}{\partial x*} \left(\frac{\partial H*}{\partial y*} \right) + \frac{\partial}{\partial y*} \left(- \frac{\partial H*}{\partial x*} \right) = 0 \tag{5}$$

Comparing Equations (4) and (5), one finds that:

$$\begin{aligned} \frac{\partial H*}{\partial y*} &= \rho c_p u * (T * - T_{ref}) - k \frac{\partial T*}{\partial x*} \\ - \frac{\partial H*}{\partial x*} &= \rho c_p v * (T * - T_{ref}) - k \frac{\partial T*}{\partial y*} \end{aligned} \tag{6a,b}$$

Moreover, for the case of no flow ($u^* = v^* = 0$), the heatlines become identical to the *heat flux lines* employed in the study of conduction heat transfer. According to Bejan (1984), the use of heatlines in convection visualization is a generalization of a standard technique (heat flux lines) used in conduction while the use of isotherms is reported as an improper way to visualize heat transfer in the field of convection. Isotherms are a proper heat transfer visualization tools only in the field of conduction (where, in fact, they have been invented) because only there they are locally orthogonal to the true direction of energy flow.

It is, unfortunately, impossible to solve the set of heatfunction equations, Equations (6a,b) analytically when the boundary conditions or the geometry is complicated. Another hindrance is when closed form solutions for velocity distribution is not available or is too complicated.

Generally, one should undertake numerical techniques to solve Equations (6a,b). One way to handle this is to find a Poisson equation by differentiating Equations (6a,b) with respect to y^* and x^*, respectively, and then eliminate the conduction terms. This is a very popular approach as in this way one is left with the following single equation:

$$\nabla^2 H* = \rho c_p \left[\frac{\partial}{\partial y*} \left(u * (T * - T_{ref}) \right) - \frac{\partial}{\partial x*} \left(v * (T * - T_{ref}) \right) \right] \quad (7)$$

This is a Poisson equation that can be rearranged in terms of vorticity and streamfunction as follows:

$$\nabla^2 H* = \rho c_p \left[\frac{\partial \psi *}{\partial y*} \frac{\partial (T * - T_{ref})}{\partial y*} + \frac{\partial \psi *}{\partial x*} \frac{\partial (T * - T_{ref})}{\partial x*} - \omega * (T * - T_{ref}) \right] \quad (8)$$

Either of the above equations, Equations (7) or (8), can be solved numerically based on the available numerical techniques. One can also use the two segregate equations, being Equations (6a) and (6b), and integrate them with respect to y^* and x^*, respectively. This approach has been used by some researchers during the past decades. One also notes that with the final form of governing equation for heatfunction (that usually comes after the momentum and thermal energy equations) being fixed, there are various numerical techniques that can be implemented, see Tannehill *et al.* (1997) for a variety of such numerical schemes for elliptic, hyperbolic, or system of equations. Commensurate with that is a number of different numerical approaches reported in the literature (Costa, 1999, 2000, 2003a, b, 2005; Costa *et al.*, 2005; Dash, 1996; De and Dalal, 2006; Deng and Tang, 2002a, b; Deng and Zhang, 2004; Deng *et al.*, 2004; Lage, 1992; Morega and Bejan, 1993, 1994; Mukhopadhyay *et al.*, 2002, 2003; Sen and Yang, 2000; Zhao *et al.*, 2007a, b; Aggarwal and Manhapra, 1989; da Silva *et al.*, 2005; Oh *et al.*, 1997; Waheed, 2006; Belloochende, 1988a, b; Incropera and DeWitt, 2002; Landau and Lifshitz, 1987; Mahmud and Fraser, 2005, 2007; Chapman, 2001; Hooman *et al.*, 2007; Hooman and Gurgenci, 2007, 2008a, b; Hooman *et al.*, 2008, 2009; Hooman and Gurgenci, 2008a, b; Mousavi and Hooman, 2006; Ejlali, 2009; Kaluri, 2009; Mobdei and Oztop, 2008).

All of the above points towards a need for more numerical analysis to find the heatfunction distribution throughout the flow region. This can be very time-consuming when large number of grids is applied. Mainly for this reason, a new method for convection visualization is to be presented in the next section that does not need numerical analysis.

Energy flux vectors

Assume that the heatlines distribution is obtainable by a function $H^*(x^*, y^*)$ as defined by Equation (6a,b). The idea is to define the vectors, to be called *Energy Flux Vectors*, which are, locally, tangent to heatlines. The role played by such vectors in heatlines visualization will be the same as the one by velocity vectors in streamlines scenario.

The gradient, $\vec{N}^* x*, y*$

$$\vec{N}^*(x*, y*) = \nabla \cdot H* = \frac{\partial H*}{\partial x*} \vec{i} + \frac{\partial H*}{\partial y*} \vec{j} \quad (9)$$

shows the vector which is normal to H^* in the two-dimensional x^* y^* plane with $\vec{i}, \vec{j}$ being the Cartesian unit vectors in x^*,y^* directions, respectively. The vector $\vec{E}^*(x*, y*)$ is normal to $\vec{N}^*(x*, y*)$ when the scalar product $\vec{E}^* \cdot \vec{N}*)$ is zero. Mathematically, this means that:

$$\vec{E}*(x*,y*) = \frac{\partial H*}{\partial y*}\vec{i} - \frac{\partial H*}{\partial x*}\vec{j} \tag{10}$$

In terms of the velocity and the temperature it reads:

$$\vec{E}^*(x*,y*) = \underbrace{\left(\rho c_p u*(T*-T_{ref}) - k\frac{\partial T*}{\partial x*}\right)}_{\text{Net energy flow in the } x* \text{ direction}}\vec{i} + \underbrace{\left(\rho c_p v*(T*-T_{ref}) - k\frac{\partial T*}{\partial y*}\right)}_{\text{Net energy flow in the } y* \text{ direction}}\vec{j} \tag{11}$$

Such vectorial definition is more analogous to *heat flow lines* or *adiabates* of conduction, as described by Incropera and Dewitt (2002), than Bejan's heatline. Observe that this vector has two components, in x^* and y^* directions, each showing the net energy (convection + conduction) in that direction. Mathematically, it makes sense to write:

$$\vec{E}^*(x*,y*) = E^*_{x*}\vec{i} + E^*_{y*}\vec{j} \tag{12}$$

with the subscript of each component showing the energy flux direction. Note also that this *energy flux vector* was called *energy flux density vector* and was used only as a basis for *energy streamline* visualization as outlined by Landau and Lifshitz (1987) and applied to different flow configurations by Mahmud and Fraser (2007). However, none of the previous studies used these vectors to *see* the flow of energy. Studies concerned with heatlines (Costa, 1999, 2000, 2003a, b, 2005; Costa *et al.*, 2005; Dash, 1996; De and Dalal, 2006; Deng and Tang, 2002a, b; Deng and Zhang, 2004; Deng *et al.*, 2004; Lage, 1992; Morega and Bejan, 1993, 1994; Mukhopadhyay *et al.*, 2002, 2003; Sen and Yang, 2000; Zhao *et al.*, 2007a, b; Aggarwal and Manhapra, 1989; da Silva *et al.*, 2005; Oh *et al.*, 1997; Waheed, 2006; Belloochende, 1988a, b) have not mentioned these vectors (only Mukhopadhyay *et al.*, 2003 used a similar concept entitled *enthalpy flux vectors* for validation of their enthalpy lines) while those on energy streamline tracking (Mahmud and Fraser, 2005, 2007; Chapman, 2001) have skipped the use of them and applied the energy streamlines for convection visualization. It should, however, be mentioned that those studies aiming at energy streamlines do still need the solution to the partial differential equation, Equation (1) of Mahmud and Fraser (2007):

$$\nabla^2 E^*_{SL} = \frac{\partial E^*_{x*}}{\partial y*}\vec{i} - \frac{\partial E^*_{y*}}{\partial x*}\vec{j} \tag{13}$$

to obtain E_{SL}* which is the shorthand notation for energy streamlines in their work. As evidenced by Equation (11) energy flux vectors are readily obtained without further need to perform a (usually demanding) numerical simulation as the required information is readily available from the solution to the momentum and the thermal energy equation.

Energy streamlines, heatlines, and energy flux vectors

Before application to certain problems, it is instructive to note that the energy flux vectors bridge the gap between the heatlines and energy streamlines, each of which extensively used for visualization purpose. As these vectors are tangent to heatlines, they show heatline paths. On the other hand, they form a basis for energy streamlines.

One should be reminded that the role played by energy flux vectors in obtaining the energy streamlines is analogous to that of vorticity in finding the streamlines. This can be verified by comparing Equation (13) with

$$\nabla^2 \psi * = \frac{\partial u*}{\partial y*} - \frac{\partial v*}{\partial x*} \tag{14}$$

Note that the right-hand-side of the above equation shows $-\omega^*$ where the vorticity, ω^*, is obtainable by taking the curl of the velocity vector.

As noted earlier, in one hand, the energy flux vectors are defined to be tangent to heatlines. On the other hand, based on streamline-velocity analogy, the energy flux vectors are tangent to energy streamlines. Hence, for two-dimensional flows energy streamlines and heatlines are effectively the same.

In view of the above, one can use energy flux vectors for convection visualization without the need for further numerical calculations. As an example, some test cases will be presented here.

Case studies

This section examines the application of energy flux vectors to certain problems solved numerically with numerical details available in Hooman *et al.* (2007, 2009) and Hooman and Gurgenci (2007, 2008a, b). As the first example, consider natural convection in a cavity (with its right wall maintained at a temperature higher than that of the left wall and horizontal adiabatic walls). Figure 1 compares the energy flux vectors and heatlines based on the results reported in Hooman *et al.* (2007). As expected, energy flux vectors are tangent to heatlines; hence, one can use them to see the heatline paths instead of going through a difficult and time-consuming separate numerical simulation. As noted earlier, considering Equations (13) and (14), one can claim that the heatlines and energy streamlines are effectively the same for two-dimensional problems. This can be easily verified by comparing the heatline and energy streamline distribution in Figure 1 with Figure 2(b) of Mahmud and Fraser (2007).

Not to be restricted to clear-fluid cases, this time a solid matrix, for which the Darcy number is $Da = 0.01$, is inserted in the cavity (Hooman *et al.*, 2007) for which the

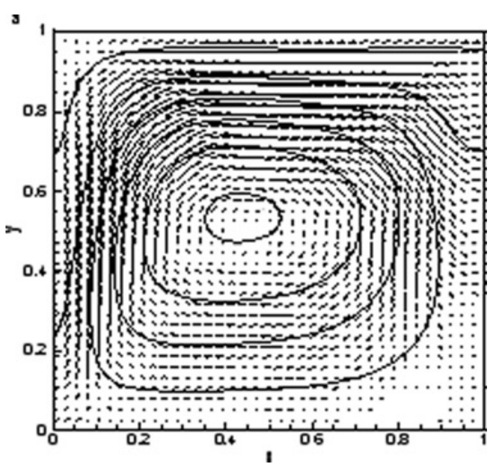
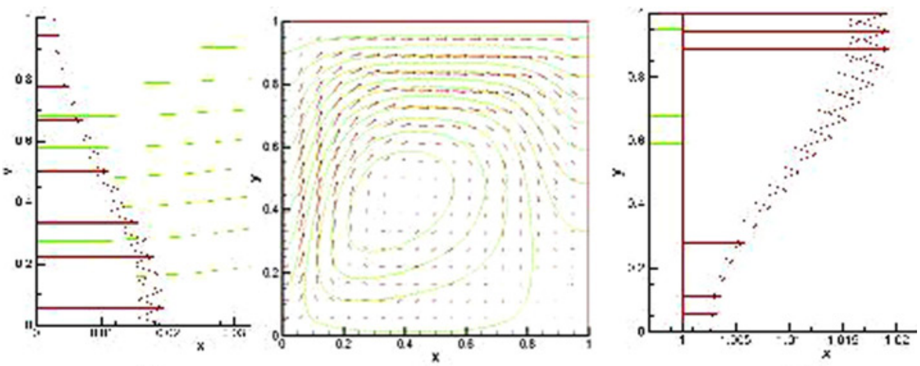


Figure 1.
Heatlines and energy flux vectors for $Ra = 10^4$

energy flux vectors and heatlines are shown in Figure 2. Once again, one observes that the energy flux vectors are equally applicable for convection visualization purpose. Another feature of considerable interest is that moving from top to bottom the sizes of the vectors are decreasing/increasing near the cooled/heated wall, as indicated by Figures 2(a) and (c), respectively. This is a unique ability of the proposed energy flux vectors. This means, according to Figure 2(a), that the heat transfer rate to the cavity is higher in the bottom half of the cavity. Figure 2(c), on the other hand, should be interpreted as an indication of higher outflow of energy at the upper part of the cavity. This could be explained by simply recalling the fact that *heat rises*. The details can be explained as follows. At the bottom of the cavity the temperature is lower than the top and this will enhance the conduction wall heat flux at the heated wall. A similar analysis may be applied to explain the reason for higher heat transfer rate in the upper half of the cavity height at the cooled (right) wall as illustrated by Figure 2(c).

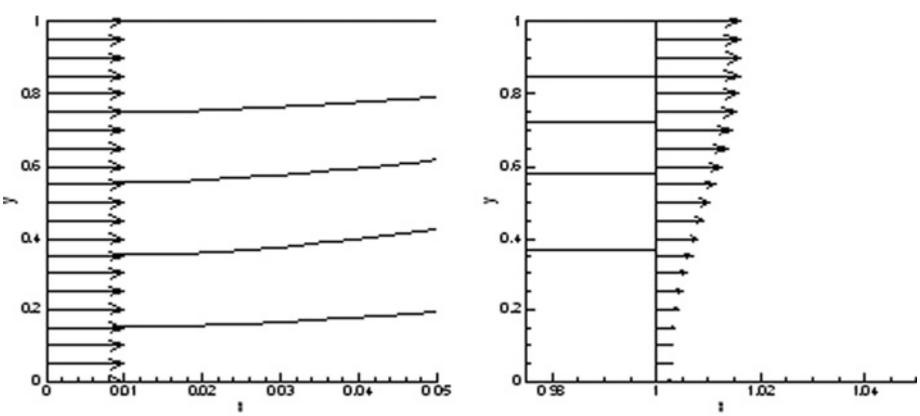
Another interesting observation is the comparison between an isothermal wall and an isoflux one. To show this in Figure 3, the left wall of the same cavity was replaced by a uniformly heated one with the right wall still at a low temperature that is used as



(a) (b) (c)

Notes: (a) Near the heated wall region, (b) whole cavity and (c) near the cooled wall region

Figure 2. Heatlines and energy flux vectors for $Ra = 10^4$



(a) (b)

Figure 3. Zoomed view of (a) the (isoflux) heated and (b) (isothermal) cooled wall, respectively

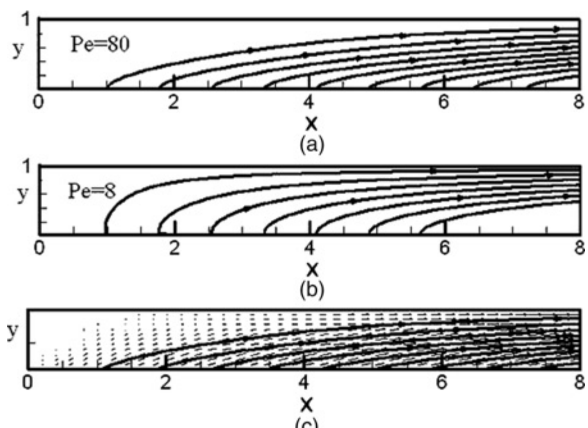
T_{ref} (see Hooman and Gurgenci, 2008a, b for more details). The isoflux Rayleigh number is $Ra_q = 10^4$. Figure 3(a) shows a zoomed view of the heated (right) wall while Figure 3(b) does the same for the isothermally cooled one. Note the uniform distribution of energy flux vectors near the isoflux wall while this uniform shape (due to uniform inlet energy to the system) is replaced by a non-uniform distribution of vectors at the cooled wall.

Finally, Figure 4 is presented to show heatlines (by drawing tangents to energy flux vectors as Figure 4(c) specifically shows) for forced convection through a uniformly heated channel. This figure illustrates the results of the developing and fully developed (both thermally and hydrodynamically) region for two different Péclet numbers. Numerical details are available in Hooman and Gurgenci (2008a, b; Hooman *et al.*, 2008) and are not repeated here for the sake of brevity. Figure 4(b) is comparable with analytical results depicted by Figures 3-19 of Bejan (2004) for the fully developed region. It should be mentioned that while the length scale used in Bejan (2004) is different from that of this study, the Péclet number of Bejan (2004) (in terms of the data used in Hooman and Gurgenci (2008a, b) and here) is $Pe = 8$. Moreover, results of this study are restricted to the bottom half of the channel due to symmetry (that can be observed in Figures 3-19 of Bejan (2004) as well).

It is fruitful to note that the commercially available software Tecplot can place streamlines on a vector field. In this study, Tecplot 360 (free trial version) was used to place streamlines (here heatlines) on the energy flux vectors. Hence, the only thing that the solver needs to do is to define the energy flux vectors in the program (a FORTRAN program in this case as used in the previous papers written by this author (Hooman *et al.*, 2007, 2008, 2009; Hooman and Gurgenci, 2007, 2008a, b)) and load it in Tecplot.

Conclusion

In this article it was mathematically shown that in two-dimensional space heatlines and energy streamlines, which were invented independently, are essentially the same as each other. Moreover, a new technique is introduced to visualize convection heat transfer. The advantage of this new technique is, on top of its higher resolution, that,



Notes: (a) Pe = 80, (b) Pe = 8 and (c) Pe = 80 (energy flux vectors and heatlines)

Figure 4.
Heatlines (obtained by flux vectors) for different Péclet numbers

contrary to heatlines and energy streamlines, it does not require further numerical calculation in addition to solving momentum and thermal energy equations. This in turn, reduces the time and the computer resources required to see the flow of energy.

References

Aggarwal, S.K. and Manhapra, A. (1989), "Use of heatlines for unsteady buoyancy-driven flow in a cylindrical enclosure", *Journal of Heat Transfer-Transactions of ASME*, Vol. 111, pp. 576-8.

Bejan, A. (1984), *Convection Heat Transfer*, 1st ed., Wiley, Hoboken, NJ.

Bejan, A. (2004), *Convection Heat Transfer*, 3rd ed., Wiley, Hoboken, NJ.

Belloochende, F.L. (1988a), "A heat function formulation for thermal-convection in a square cavity", *Computational Methods in Applied Mechanics and Engineering*, Vol. 68 No. 2, pp. 141-9.

Belloochende, F.L. (1988b), "A heat function formulation for thermal-convection in a square cavity", *International Communications in Heat and Mass Transfer*, Vol. 15 No. 2, pp. 193-202.

Chapman, C.J. (2001), "Energy paths in edge waves", *Journal of Fluid Mechanics*, Vol. 426, pp. 135-54.

Costa, V.A.F. (1999), "Unification of the streamline, heatline and massline methods for the visualization of two-dimensional transport phenomena", *International Journal of Heat and Mass Transfer*, Vol. 42 No. 1, pp. 27-33.

Costa, V.A.F. (2000), "Heatline and massline visualization of laminar natural convection boundary layers near a vertical wall", *International Journal of Heat and Mass Transfer*, Vol. 43 No. 20, pp. 3765-74.

Costa, V.A.F. (2003a), "Unified streamline, heatline and massline methods for the visualization of two-dimensional heat and mass transfer in anisotropic media", *International Journal of Heat and Mass Transfer*, Vol. 46 No. 8, pp. 1309-20.

Costa, V.A.F. (2003b), Comment on the paper by Qi-Hong Deng, Guang-Fa Tang, "Numerical visualization of mass and heat transport for conjugate natural convection/heat conduction by streamline and heatline", *International Journal of Heat and Mass Transfer*, Vol. 46 No. 1, pp. 185-6.

Costa, V.A.F. (2005), "Momentum functions and momentum lines for fluid flow visualization and analysis", *International Journal of Heat and Mass Transfer*, Vol. 48 No. 10, pp. 2064-78.

Costa, V.A.F., Oliveira, M.S.A. and Sousa, A.C.M. (2005), "Laminar natural convection in a vertical stack of parallelogrammic partial enclosures with variable geometry", *International Journal of Heat and Mass Transfer*, Vol. 48 Nos 3/4, pp. 779-92.

da Silva, A.K., Lorente, S. and Bejan, A. (2005), "Constructal multi-scale structures with asymmetric heat sources of finite thickness", *International Journal of Heat and Mass Transfer*, Vol. 48, pp. 2662-72.

Dash, S.K. (1996), "Heatline visualization in turbulent flow", *International Journal of Numerical Methods for Heat & Fluid Flow*, Vol. 6 No. 4, pp. 37-46.

De, A.K. and Dalal, A. (2006), "A numerical study of natural convection around a square, horizontal, heated cylinder placed in an enclosure", *International Journal of Heat and Mass Transfer*, Vol. 49 Nos 23/24, pp. 4608-23.

Deng, Q.H. and Tang, G.F. (2002a), "Numerical visualization of mass and heat transport for conjugate natural convection/heat conduction by streamline and heatline", *International Journal of Heat and Mass Transfer*, Vol. 45 No. 11, pp. 2373-85.

Deng, Q.H. and Tang, G.F. (2002b), "Numerical visualization of mass and heat transport for mixed convective heat transfer by streamline and heatline", *International Journal of Heat and Mass Transfer*, Vol. 45 No. 11, pp. 2387-96.

Deng, Q.H. and Zhang, G.Q. (2004), "Indoor air environment: more structures to see?", *Building Environment*, Vol. 39 No. 12, pp. 1417-25.

Deng, Q.H., Zhou, J.M., Mei, C. and Shen, Y.M. (2004), "Fluid, heat and contaminant transport structures of laminar double-diffusive mixed convection in a two-dimensional ventilated enclosure", *International Journal of Heat and Mass Transfer*, Vol. 47 No. 24, pp. 5257-69.

Ejlali, A., Ejlali, A., Hooman, K. and Gurgenci, H. (2009), "Application of high porosity metal foams as air cooled heat exchangers to high heat removal systems", *International Communications in Heat and Mass Transfer*, Vol. 36 No. 7, pp. 674-9.

Hooman, K. and Gurgenci, H. (2007), "Effects of viscous dissipation and boundary conditions on forced convection in a channel occupied by a saturated porous medium", *Transport in Porous Media*, Vol. 68, pp. 301-19.

Hooman, K. and Gurgenci, H. (2008a), "Heatline visualization of natural convection in a porous cavity occupied by a fluid with temperature dependent viscosity", *ASME Journal of Heat Transfer*, Vol. 130, paper # 012501.

Hooman, K. and Gurgenci, H. (2008b), "Effects of temperature-dependent viscosity on forced convection inside a porous medium", *Transport in Porous Media*, Vol. 75, pp. 249-67.

Hooman, K., Gurgenci, H. and Dincer, I. (2007), "Heatline visualization of natural convection in a porous cavity occupied by a fluid with temperature dependent viscosity", *Second Int. Conf. Porous Media Applications in Science, Engineering and Industry, Kauai, HI, 17-21 June*.

Hooman, K., Gurgenci, H. and Dincer, I. (2009), "Heatline and energy flux vectors visualization of natural convection in a porous cavity occupied by a fluid with temperature-dependent viscosity", *Journal of Porous Media*, Vol. 12, pp. 265-75.

Hooman, K., Hooman, F. and Mohebpour, S.R. (2008), "Entropy generation for forced convection in a porous channel with isoflux or isothermal walls", *International Journal of Exergy*, Vol. 5, pp. 78-96.

Incropera, F.P. and DeWitt, D.P. (2002), *Fundamentals of Heat and Mass Transfer*, 5th ed., Wiley, New York, NY.

Kaluri *et al.* (2009), "Bejan's heatlines and numerical visualization of heat flow and thermal mixing in various differentially heated porous square cavities", *Numerical Heat Transfer A*, Vol. 55, pp. 487-516.

Kimura, S. and Bejan, A. (1983), "The heatline visualization of convective heat-transfer", *Journal of Heat Transfer Transactions of ASME*, Vol. 105 No. 4, pp. 916-9.

Lage, J.L. (1992), "Effect of the convective inertia term on Benard convection in a porous-medium", *Numerical Heat Transfer Part A (Applications)*, Vol. 22 No. 4, pp. 469-85.

Landau, L.D. and Lifshitz, E.M. (1987), *Fluid Mechancis*, 2nd ed., Pergamon Press, New York, NY.

Mahmud, S. and Fraser, R.A. (2005), "Flow, thermal, and entropy generation characteristics inside. A porous channel with viscous dissipation", *International Journal of Thermal Sciences*, Vol. 44 No. 1, pp. 21-32.

Mahmud, S. and Fraser, R.A. (2007), "Visualizing energy flows through energy streamlines and pathlines", *International Journal of Heat and Mass Transfer*, Vol. 50 Nos 19/20, pp. 3990-4002.

Mobdei, M. and Oztop, H.F. (2008), "Visualization of heat transport using dimensionless heat function for natural convection and conduction in an enclosure with thick solid ceiling", *Computers & Mathematics with Applications*, Vol. 56, pp. 2596-608.

Morega, A.M. and Bejan, A. (1993). "Heatline visualization of forced-convection laminar boundary-layers", *International Journal of Heat Mass Transfer*, Vol. 36 No. 16, pp. 3957-66.

Morega, A.M. and Bejan, A. (1994). "Heatline visualization of forced-convection in porous-media", *International Journal of Heat and Fluid Flow*, Vol. 15 No. 1, pp. 42-7.

Mousavi, S.S. and Hooman, K. (2006), "Heat and fluid flow in entrance region of a channel with staggered baffles", *Energy Conversion Management*, Vol. 47, pp. 2011-9.

Mukhopadhyay, A., Qin, X., Aggarwal, S.K. and Puri, I.K. (2002), "On extension of 'heatline' and 'massline' concepts to reacting flows through use of conserved scalars", *Journal of Heat Transfer-Transactions of ASME*, Vol. 124 No. 4, pp. 791-99.

Mukhopadhyay, A., Qin, X., Puri, I.K. and Aggarwal, S.K. (2003), "Visualization of scalar transport in nonreacting and reacting jets through a unified 'heatline' and 'massline' formulation", *Numerical Heat Transfer Part A (Applications)*, Vol. 44 No. 7, pp. 683-704.

Oh, J.Y., Ha, M.Y. and Kim, K.C. (1997), "Numerical study of heat transfer and flow of natural convection in an enclosure with a heat-generating conducting body", *Numerical Heat Transfer Part A (Applications)*, Vol. 31 No. 3, pp. 289-303.

Sen, M. and Yang, K.T. (2000), "Laplace's equation for convective scalar transport in potential flow", *Proceedings of the Royal Society of London Series A (Mathematical, Physical and Engineering Sciences)*, Vol. 456 No. 2004, pp. 3041-5.

Tannehill, J.C., Anderson, D.A. and Pletcher, R.H. (1997), *Computational Fluid Mechanics and Heat Transfer*, 2nd ed., Taylor & Francis, Washington, DC.

Waheed, M.A. (2006), "Temperature dependent fluid properties effects on the heat function formulation of natural convective flow and heat transfer", *International Journal of Numerical Methods for Heat & Fluid Flow*, Vol. 16 Nos 2/3, pp. 240-60.

Zhao, F.Y., Liu, D. and Tang, G.F. (2007a), "Application issues of the streamline, heatline and massline for conjugate heat and mass transfer", *International Journal of Heat and Mass Transfer*, Vol. 50 Nos 1/2, pp. 320-34.

Zhao, F.Y., Liu, D. and Tang, G.F. (2007b), "Conjugate heat transfer in square enclosures", *Heat and Mass Transfer*, Vol. 43 No 9, pp. 907-22.

About the author

Kamel Hooman is a Lecturer in Mechanical Engineering at The University of Queensland. Being involved in such versatile research areas as convection in porous media, bio-fluid mechanics, mine ventilation, MEMS, and CFD, he has recently shifted his attention to renewable energy with his research activities being mainly centered on dry cooling for geothermal power plants. Kamel Hooman can be contacted at: k.hooman@uq.edu.au