Heatlines (1983) versus synergy (1998)

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ABSTRACT

A picture is worth a thousand words. This article is about a picture known as “heatlines” since 1983, and “synergy” since 1998. Both concepts, heatlines and synergy, are about visualizing the physics of convection, which is the combination (superposition) of heat conduction lines and enthalpy flow lines over a material in motion. Heatlines and synergy are reviewed here comparatively. This comparison reveals that synergy is a remake of heatlines, and that synergy has no physical connection with heat transfer enhancement. At bottom, it has become a lot easier to take an existing idea change some key words and drawings and publish the old idea as new.

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1. Visualization of convection

“Few discoveries are more irritating than those which expose the pedigree of ideas” (Lord Acton).

In the spring of 1982, while injured in a basketball game and writing notes for overhead projection in my course on convection, I had the idea of “heatlines” [1,2] as a method to visualize the true direction of heat flow in convection (this story is told in the Preface to Ref. [3]). The heatline direction is “true” because it is the *resultant* of two energy currents, heat conduction and enthalpy carried by the mass flow.

I wrote this idea was for the opening pages of the 1984 edition of my convection book [1]. The disclosure was with reference to the general two-dimensional laminar convection configuration summarized here in Section 2. To illustrate the lines that result from combining the heat flux lines and the streamlines, I proposed to my doctoral student Shigeo Kimura to plot the heatlines for natural convection in the classical configuration of a two-dimensional enclosure heated from one side and cooled from the other. My paper with Kimura [2] appeared a few months before my book [1]. In 1987, my doctoral student Osvaldo Trevisan and I extended the concept to “masslines” for visualizing mass transfer by convection [4].

Heatlines and masslines were adopted. The early adoptions were reviewed in Costa [5] and the second edition of my convection book [6], which appeared in 1995. Important is that

in these reviews one could see Fig. 1: the heatlines in duct flow and boundary layer flow, which I had published with my doctoral student Alexandru Morega in 1993 [7,8]. New heatlines are being published regularly, as shown in the extensive bibliography compiled in the most current publications, for example, Refs. [9,10].

2. Heatlines

The opportunity to see the physics of a problem is essential to a problem-solver's ability to learn from his experience and, in this way, to improve his technique. In convection problems, it is important to visualize the flow of fluid and, riding on this, the flow of energy. For example, in the two-dimensional Cartesian configuration it has been common practice to define a streamfunction $\psi(x, y)$ as

$$u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x} \quad (1)$$

such that the mass continuity equation for incompressible flow is satisfied identically,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2)$$

The flow of fluid follows the path indicated by the $\psi = \text{constant}$ line passing through the point of interest. Therefore, although there are no substitutes for (u, v) as bearers of precise information regarding the local flow, the family of $\psi = \text{constant}$ streamlines provides a bird's-eye view of the entire flow field.

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Nomenclature

c_p	specific heat at constant pressure, $\text{J kg}^{-1} \text{K}^{-1}$
H	heatfunction, W m^{-1}
k	thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$
$\dot{q}$	heat source, W m^{-3}
T	temperature, K
u, v	fluid velocity, m s^{-1}

x, y coordinates, m

Greek symbols

α	thermal diffusivity, $\text{m}^2 \text{s}^{-2}$
ρ	density kg m^{-3}
ψ	streamfunction, $\text{m}^2 \text{s}^{-1}$

In convection, the transport of energy through the flow field is a combination of both thermal diffusion and enthalpy flow. For any such field, we defined [1,2] a new function $H(x, y)$ such that the net flow of energy (thermal diffusion and enthalpy flow) is zero across each $H = \text{constant}$ line. The heatfunction H is defined such that it satisfies the energy equation identically. For steady-state two-dimensional convection through a constant-property homogeneous fluid,

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (3)$$

or

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

the heatfunction is defined as

$$\begin{aligned} \frac{\partial H}{\partial y} &= \rho c_p u (T - T_{\text{ref}}) - k \frac{\partial T}{\partial x}, \quad (\text{net energy flow in the } x \text{ direction}) \end{aligned} \quad (5)$$

$$\begin{aligned} -\frac{\partial H}{\partial x} &= \rho c_p v (T - T_{\text{ref}}) - k \frac{\partial T}{\partial y}, \quad (\text{net energy flow in the } y \text{ direction}) \end{aligned} \quad (6)$$

so that the heatfunction $H(x, y)$ satisfies Eq. (3) identically. Note that the definition above also applies to convection through a fluid-saturated porous medium, where Eq. (3) accounts for energy conservation (cf., Ref. [3], chapter 12). The reference temperature T_{ref} is an arbitrary constant that can be selected based on convention. Patterns of $H = \text{constant}$ heatlines are instructive when T_{ref} is chosen as the lowest temperature that occurs in the heat transfer configuration. For a meaningful comparison of the heatlines of one flow with the heatlines of another flow, I proposed the convention that T_{ref} be set equal to the lowest temperature of the flow field.

Heatlines are descriptions of how heat flows in a *specified* flow configuration, geometry and boundary conditions together. The value of the heatfunction at the wall is the total heat transfer rate, or the Nusselt number for that configuration. If you want easier flowing of energy through, then you should allow the configuration to morph to provide easier access to the currents that flow through it. This next step (the constructal law of design and evolution in nature) was published on 1 November 1996 [11] and in the summer of 1997 in the second edition of my thermodynamics book [12].

In Refs. [1,2], I also pointed out that if the fluid flow subsides ($u = v = 0$), the heatlines become identical to the heat-flux lines employed frequently in the study of conduction phenomena. Therefore, as a heat transfer visualization technique, the use of heatlines is the generalization of a standard technique (heat-flux lines) used in conduction. I further noted that the contemporary use of $T = \text{constant}$ lines is not appropriate to visualize convection:

isotherms are appropriate only for conduction (where, in fact, they have been invented) because only there are they locally orthogonal to the direction of energy flow. The use of $T = \text{constant}$ lines to visualize convection heat transfer makes as much sense as using $P = \text{constant}$ lines to visualize fluid flow.

The duct flow and boundary layer flow versions of this formulation are simpler, because these flow regions are *slender* [1], and as a consequence v is small when compared with u . In 1993 we showed [7] that Eqs. (3)–(6) are replaced by

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2} \quad (7)$$

$$\frac{\partial}{\partial x} (\rho c_p u T) + \frac{\partial}{\partial y} \left(\rho c_p v T - k \frac{\partial T}{\partial y} \right) = 0 \quad (8)$$

$$\frac{\partial H}{\partial y} = \rho c_p u (T - T_{\text{ref}}) \quad (9)$$

$$\frac{\partial H}{\partial x} = \rho c_p v (T - T_{\text{ref}}) - k \frac{\partial T}{\partial y} \quad (10)$$

Because of the slenderness of the flow region, the heatlines are relatively flat and almost parallel to the heated or cooled wall. See Fig. 1, which was also present in the 1995 edition of my convection book [6], and keep it in mind as you read the next section and look at Fig. 2.

3. Synergy

Synergy (in Greek, and modern Latin) means joint work, or combined cooperative action. In 1998, this word was proposed by Z.Y. Guo with B.X. Wang (editor of this journal) [13] to indicate the collaboration of conduction with enthalpy flow in convection. Guo et al. [13] did not start with the full two-dimensional convection, as in Eqs. (3)–(6). Instead, they used the simpler version, from my 1993–1995 work: the duct flow [7,8], Eqs. (7)–(10). They rewrote Eq. (7) as

$$-\frac{\dot{q}}{k} = \frac{\partial^2 T}{\partial y^2} \quad (11)$$

where $\dot{q}$ is shorthand for a heat source due to enthalpy flow,

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = -\frac{\dot{q}}{\rho c_p} \quad (12)$$

The fact that Eqs. (11) and (12) add nothing new to the existing version is obvious. The only novelty was that enthalpy flow component of heatlines was renamed $\dot{q}$. To mask this, Guo et al. [13] made reference to six old books [14–19] that had absolutely nothing to do with visualizing the distinction (or collaboration) between thermal diffusion and enthalpy flow lines in convection.

A picture is worth a thousand words indeed. Compare Fig. 1 with Fig. 2. In the “synergy” version, Guo et al. [13] made three points:

Fig. 1. Heatlines in fully developed laminar duct flow [6,8].

1. Heat flow by conduction and fluid flow (enthalpy flow) are “analogous”. This is not true. The former is driven by a temperature difference, and the latter by a force (wall friction, pressure difference, buoyancy). When the force is zero, the enthalpy flow is absent, while the heat current by thermal diffusion persists.
2. The direction of the heat flux lines is not the same as the direction of the streamlines, which are the fluid (or enthalpy) flow lines. This is true. This was the whole idea behind “heatlines”, fifteen years before Guo et al.’s translation of heatlines into synergy.
3. The flow of heat through the convective medium can be increased by increasing the angle (β , Fig. 2) between the heat flux lines and the streamlines. This is wrong, obviously: the maximum β is 180° , and it occurs on the centerline ($r = 0$, Fig. 2), which is hardly the locus of intense heat transfer. The angle β is not a degree of freedom, a knob to be turned by the designer. There is an infinity of angles β distributed throughout the flow field, and each β depends on its neighbors (β is a field).

The distribution of β ’s is one, and it is fixed, just like the distribution of T and (u, v) in the specified flow configuration.

Points 1 and 2 and their associated figures are from the heatlines literature, although Guo et al. [13] made no reference to the heatlines literature. Point 3 is a diversion, because the designer has no idea of the local angles between heat flux lines and stream flow lines in a multi-dimensional flow field. The designer knows even less about how to change the angles, which angles in what places, and whether the change in a local angle means a change of opposite sign in a neighboring angle, or an increase in the global heat transfer rate. The β ’s are not accessible to the designer.

4. Augmentation

Guo et al. [13] proposed their β -maximization as a “novel concept of heat transfer enhancement”. This claim has no physical

Fig. 2. Guo et al.'s [13] isotherms and streamlines in fully developed laminar duct flow. Top: wall with uniform heat flux; Bottom: isothermal wall.

basis because enhancement requires a change in the flow configuration, whereas in Guo et al.'s straight duct (Fig. 2, with specified Re and Pr) nothing changes. The necessary “change” is the new geometry that replaces the old geometry. Interestingly enough, in their conclusion, Guo et al. [13] had a brief statement about the use of a “contracting” (sic) duct to accelerate the flow, and “special inserts”, but that was the extent of the claimed novel concept of heat transfer enhancement. Flow acceleration and inserts were not new in 1998.

Fig. 3 shows a classical example of how a change in geometry causes enhancement of heat flow. Fig. 3a shows the heat flux lines of conduction through the body of a fin with rectangular profile [20]. Can the geometry be changed such that the conduction path poses less resistance? Ernst Schmidt (1892–1975) answered this question in 1926. Inside a fin, he imagined one “heat tube” between two heat flux lines, and pointed out that a tube that is pinched at one end is not the best tube. His proposal was to *reshape* the fin such that all its heat tubes have constant cross-sections (i.e., no strangulations—intuitively, he had the same vision as the one expressed as the constructal law). This led him to the new geometry sketched in Fig. 3b (also from Ref. [20]): the fin thickness δ is proportional to x^2 , where x increases from the sharp tip toward the base of the fin. The lowest resistance to conduction along the fin belongs to the fin with parabolic profile.

Fins with razor-sharp tips are not practical, yet, the evolution of fin shapes has been from Fig. 3a and b. Practical designs today resemble Fig. 3b, without the zero-thickness tip. The more efficient and strong fins have triangular and trapezoidal profiles. An amazing diversity of two-dimensional and three-dimensional fin

geometries has been emerging. Each new geometry represents “design change”, new knowledge, and technology evolution [21].

The emptiness of the claim that “synergy” is a novel concept for heat transfer enhancement is richly documented in the subsequent papers that repeated the claim. Take for example the 2014 paper by Ma et al. [22] which documents the effect of various twisted tape inserts on heat transfer (Q/Q_0 , Nu/Nu_0) and fluid friction ($\Delta P/\Delta P_0$, f/f_0), where 0 indicates the bare tube, as reference configuration. None of this is new, in view of the work from 1970 to 1990 (Bergles, Webb, Bejan). At the end of their long paper, Ma et al. [22] show that the twisted tape inserts also have an effect on the “synergy angle β ” (singular, i.e., one angle!, which is not defined anywhere).

If one has all the information on the effect of twisted-tape design on heat transfer (Q/Q_0 , Nu/Nu_0) and fluid friction ($\Delta P/\Delta P_0$, f/f_0), then why would anyone need to know one β , or any β at all? There is no reason for this, physical or practical, in spite of the “physical quantity” label added to “synergy” in the title of Ref. [22], and earlier by Guo et al. in Ref. [23].

One of the reviewers of the present article brought up an even better example [24] of the false claim that synergy is a design concept for heat transfer enhancement. The authors of Ref. [24] mention the synergy principle and several kinds of angles (velocity field, pressure gradient), and reports the Nu and f ratios mentioned above, which are Webb's performance evaluation criteria (PEC). They reach two nonsensical conclusions: the changes in the synergy angle β point against higher PEC and the other synergy angle (θ) is better when it changes the other way. This means that β and θ affect performance in opposite ways. Then, how can synergy be

Fig. 3. The evolution of the design (configuration) from (a) to (b) leads to heat transfer augmentation: slender fins, drawn here after Figs. 2.17 and P2.19 of Ref. [20].

taken seriously? The authors themselves [24] state clearly that the analysis would suffice if based solely on PEC. The reviewer of the present article concludes by questioning “how a secondary flow field can be “chosen” or “designed” in order to promote heat transfer augmentation”.

5. Conclusion

This comparative review of the heatlines and synergy concepts showed that synergy is not original: it is a repeat of the heatlines idea. Those who might think that the similarities between synergy and heatlines (e.g., Fig. 2 versus Fig. 1) are purely coincidental should take note of the following pattern:

The lead author of the synergy version (Z.Y. Guo) has used the same publishing technique several times since, and each time he was exposed on the basis of stringent anonymous peer review:

- (i) Guo's Ref. [25] was so much like a paper published by our group [26] that we wrote a letter to the editors [27] in which we charged that Ref. [25] is “so very similar that it cannot be a coincidence”. Our letter was reviewed by three anonymous reviewers who agreed unanimously with our charge. On that basis our letter was published [27].
- (ii) Six independent papers in a single year [28–33] revealed that Guo's quantity “entransy” [34] is a falsehood, and that it is a technique for duplicating ideas and results that were obtained previously based on known methods such as entropy generation minimization, exergy destruction minimization and constructal theory. Manjunath and Kaushik [32] concluded on page 359 that entransy papers are “rip offs of existing publications”. Oliveira and Milanez [33] concluded on page 525 that “the results obtained by the entransy concept are identical to those obtained by the entropy generation technique”.
- (iii) Guo's “uniformity principle of temperature field difference” in a heat exchanger [35] was published 23 years earlier (and in general form) in Ref. [36]. This duplication was exposed based on peer review in Refs. [30,32].
- (iv) Guo's construction of trees [37] of high conductivity material in a low conductivity background is a remake of Refs. [11,12,38], and it is (physically and mathematically) identical to the evolution of diffusion architecture as the birth of trees of high permeability in a low permeability background, published originally in Refs. [38,39]. This duplication was exposed based on peer review in Ref. [30].

At bottom, the present article is about how ideas spread [40], how sometimes they are given new names to mask their pedigree, and about the power of members of national academies [41]. Indeed, it is becoming a lot easier to take an existing idea, change some keywords and figures, and publish the idea as novel.

Conflict of interest

None declared.

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