International Journal of Heat and Mass Transfer 118 (2018) 1069–1079

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Review

# Heatlines and other visualization techniques for confined heat transfer systems

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ARTICLE INFO

*Article history:*
Received 25 July 2017
Received in revised form 10 November 2017
Accepted 14 November 2017

*Keywords:*
Convective heat transfer
Visualization techniques
Heatlines
Energy flux vectors
POD

ABSTRACT

Efficient visualization techniques are required to understand the flow physics for any numerical simulation. For convective heat transfer problems, most widely used techniques to visualize the fluid flow and heat transfer are streamlines and isotherms respectively. These methods are not sufficient to address the degrees of complexity associated with the complicated convective problems. Thus, different visualization techniques have been developed to represent the results depending on the problem. In this article, an effort has been made to collate visualization techniques in literature for convective heat transfer system like, heatlines, energy streamlines, energy flux vectors, proper orthogonal decomposition (POD), Poincare map etc. The fundamentals of different techniques are briefly discussed, applications of these techniques are shown with proper examples. The usefulness and limitations of these techniques are also discussed. Heatline is found to be the best visualization tool for two dimensional steady situations. However, in 3D and transient scenario Lagrangian approach or POD can be used.



**Contents**



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https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.075
0017-9310/

## 1. Introduction

Advancement of numerical modeling techniques helps in solving the complex nature of the convective heat transfer problems. Compared to the experimental results, it is easier to get information for all primitive variables from numerical studies. The physical state of the systems is generally represented by the primitive variables like temperature, velocity or pressure. However, to get physical insight of the convective heat transfer problems efficient numerical visualization techniques should be followed. This will help in extracting the appropriate information of the problem and will also help to explain the results. For complex flow behavior characterization, extra care is needed not only in the analysis but also in the visualization of the flow. It should be noted that proper visualization technique needs to be chosen to eliminate any false interpretation of the results.

Streamlines, isotherms and velocity vectors are the most popular visualization techniques for the numerical simulation. Apart from streamlines, the other two can be plotted directly from the primary variables using suitable plotting softwares. Reserchers have developed different visualization tools to explain the flow physics and behavior of the system. Kimura and Bejan [1] proposed a visualization technique for convective heat transfer using heatfunction and heatlines. Heatlines help in visualization of the energy flow in the domain. The methodology has been extended by others [2–8]. Heatlines have been used in different type of problems like, convective heat transfer [7,9,10], weak unsteady problem [3], reacting flows [5], turbulent flows [11] etc. Costa [4,6] presented a unified approach for visualization by considering the physical and numerical aspects of the heatfunction and heatlines in a conjugate transport problem. Mahmud and Fraser [12] introduced an alternative visualization technique for convective heat transfer called energy streamlines. Transport of different other forms of energy like thermal, electrical, chemical, magnetic, potential and kinetic energy are considered in the energy streamlines. Hooman [13] introduced another visualization tool called energy flux vectors to bridge the gap between the heatlines and energy streamlines. These vectors are tangent to the heatlines and represents the flow of energy for a two dimensional system. Energy flux vectors have been used in different types of flow configurations [14–18], although this does not give any quantitative estimation of energy transfer. The limitations and usefulness of heatlines and other methods will be discussed in details afterward.

Guo et al. [19] demonstrated "field synergy principle" concept by presenting an analogy between conduction and convection. According to this theory the included angle of the velocity vector and the temperature gradient at intersection is an important parameter for estimating heat transfer enhancement. This concept of field synergy was further improved and used by several researchers [20–22]. However, Bejan [23] pointed out that the 1983 concept of "heatlines" reappeared in 1998 under the new name of "synergy". This topic is discussed later in this paper.

Streamfunction and streamlines are generally used to describe the momentum transport during fluid flow [24]. For analyzing steady two dimensional flow visualization, Costa [25] proposed a visualization tool using momentum function and momentum lines. In this method, two momentum function are defined, one in each momentum direction. The momentum vectors and the momentum lines provide the information related to momentum transport and interacting forces. Momentum function requires steady momentum equations, that can be presented in a divergence-free form. This also implies that the method would not work in presence of source terms like body forces unless the source term itself can be expressed in a divergence free form. In a convective heat transfer system specifically during natural convection or flow through porous media, it is not possible to define momentum function. The details of this function and solution methodology will not be discussed in this article due to its limited applications. Interested readers can find the details in [25].

Proper orthogonal decomposition (POD) is a low order modeling technique to identify the coherent structures and energetic modes that represent the flow behavior. The inherent dynamics of the systems can be studied by using POD. POD has been used extensively in many areas [26–28]. Ding et al. [26] used snapshot method of POD on numerical data for faster result generations. They showed the use of POD for interpolating results at off-design parameters. Mahapatra et al. [29] used POD to identify the modal structure and the related energies in an alternately active localized heat source in a confined convective system. In the coherent structures if temporal periodicity is observed then spectral methods like Dynamic mode decomposition (DMD) needs to be used. DMD differentiates the modes based on the linear amplification [30]. The extension of DMD proposed by Williams et al. [31] can be used for decomposing nonliear dataset. In highly turbulent flow, the frequency of a single coherent structure becomes variable and due to the presence of other intermittent structures, the decomposition becomes difficult. The intermediate decompositions between the above two extrema can be obtained from spectral proper orthogonal decomposition (SPOD) [30]. The detailed discussion about these methods are out of the scope of this work.

There are already existing techniques to numerically visualize the data. However, the information about many of them are somewhat scattered in the literature, limiting their effective use in different heat transfer problems. For example, even though it is known that isotherms will not properly represent the convective heat transfer situations, isotherms are generally used more frequently than heatlines although the concept of heatlines have been available for more than three decades. The present review highlights the limitations and usefulness of heatlines and other visualization tools that can be used depending on the situations. This review provides the description of different techniques available for convective heat transfer with suitable examples, including our own results. For example, for weak transient scenario, heatlines can be used, but energy flux vectors will be a better choice in case of a transient scenario. However, energy flux vectors, like velocity vectors, do not provide the same level of quantitative information as heatlines. Similarly, recent literature shows development of visualization tools like Lagrangian tracking, Poincare maps, and modal decomposition techniques that can be useful for transient and three-dimensional problems where heatlines cannot be used. In addition, there are recent extensions of the concept of heatlines to problems with source terms, which are also beyond the original formulation of heatlines. The purpose of the present review is to present all these techniques in a unified, coherent manner which can be of utility to computational heat transfer community, especially in extracting useful information from problems with complex physics. A very brief description of the fundamentals of different visualization techniques are presented in Section 2; the suitability of different techniques are discussed in Section 3; different techniques are illustrated with appropriate examples in Section 4 and finally the conclusions and future road map are pointed out in Section 5.

## 2. Fundamentals of visualization techniques

### 2.1. Heatlines and streamlines

Heatfunction incorporates both conductive and convective heat fluxes. The total flow of energy across each heatline is zero. After