International Journal of Heat and Mass Transfer 92 (2016) 349–359

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A study of entropy generation in tree-shaped flow structures

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ARTICLE INFO

Article history:
Received 13 June 2015
Received in revised form 21 August 2015
Accepted 22 August 2015
Available online 14 September 2015

Keywords:
Tree-shaped flow structures
Entropy generation
Power-law fluid
Porous tubes
Obstructed/blocked tubes
Hess–Murray law

ABSTRACT

This paper examines the degree of irreversibility, or thermodynamic nonideality, in a tree-shaped flow network with a constant wall heat flux. The tree network is a dichotomic and homothetic structure, and a fully developed laminar flow of Newtonian and non-Newtonian power law fluids is assumed. We investigate (i) the characteristics of the tubes composing the network (i.e., variation in the homothetic ratios of length and diameters, as well as variation in wall permeability of tubes), (ii) the existence of blocked (obstructed) tubes in the network, (iii) fluid characteristics, and (iv) frictional and thermal effects on entropy generation. The influence of parameters like the fluid behavior index, Reynolds number, Nusselt number, homothety ratios for length and diameters, and wall permeability is hence evaluated. Finally, the degree of thermodynamic irreversibility associated to tree networks designed for a maximum flow access is determined.

1. Introduction

Tree-shaped flow networks are omnipresent in Nature and cover every scale from the network of tiny tubes in plants and mammals, to rivers basins and deltas [1–4]. This design finds also application in engineered systems [5–13]. Biomimetic microvascular networks for efficient fluid transport are used in several technological applications.

Research on tree flow structures, though dating back one century [1–3], is still a topic of great interest due to their widespread applications. In complex biological organism, tree-shaped flow networks serve a fundamental purpose of transport functional fluids to tissues. Within this context, many crucial functions are performed, such as delivery of nutrients and removal of waste, and damage inhibition and repair. The pioneering work of Hess [2] and Murray [3] analyzed the distribution of blood vessel sizes of circulatory system. They found that the cube of the diameter of the parent tube equals the sum of the cubes of the diameters of both daughter tubes. This third-power rule (Hess–Murray law) was justified based on the principle of minimum power [3]. Bejan and co-authors [1,14,15] show that the best flow path that connects one point with infinity of points (line, area, or volume) is a network bifurcating on several levels. They relied on the constructal law to derive Hess–Murray law (i.e., minimization of the hydraulic resistance subject to the total volume constraint) and they concluded that the lengths of the daughter tubes also obey to a third-power rule. These studies consider that the flow of fluid through the tubes is described by the Hagen–Poiseuille equation (creeping flow). As mentioned, tree-shaped flow structures are also of common appearance in inanimate flow systems such as river basins and deltas. Empirical evidences led geomorphologists to propose a number of scaling laws that indicate that some properties of river basins are invariant [16,17]. These geophysical networks also generate their area-to-point flow configuration in accordance with minimization of flow resistance subject to the volume constraint [14,15].

For creeping flow or Stokes flow through tubes, viscous dissipation occurs due to the existence of the frictional dissipation arising from the fluid-walls contact, and due to the internal dissipation associated with the mechanical power needed to transport the fluid through the tubes. The generation of entropy may occur due to viscous dissipation and heat transfer. The Gouy–Stodola theorem states that the entropy produced by irreversibility in a process is proportional to the loss of exergy [18,19]. Therefore, a decrease of entropy generation means a decrease of irreversibility (or less loss of exergy), and the most efficient processes achieve the minimum entropy generation rates. The improvement of performance of a system means a design that provides a minimum entropy generation rate. The entropy generation minimization method [18] is a well-established procedure to minimize the thermodynamics irreversibilities of a system subject to a specified set of constraints, and to compare different designs. An important number of researches deal with the best design of systems based on

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.08.067
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minimal entropy generation principle (see, for example the review papers of [20–23]). Studies connecting the flow configuration of tree networks to their entropy production are presented in Refs. [24–26].

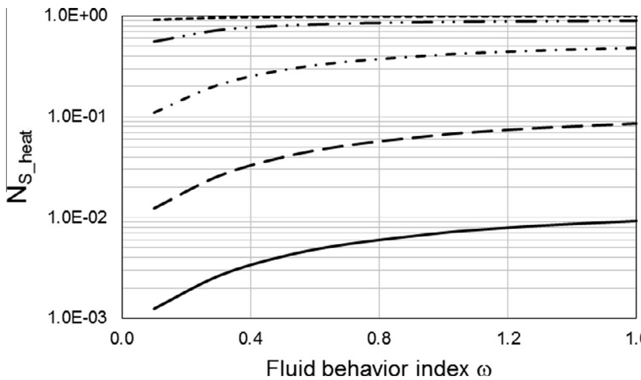

Fig. 1. Entropy generation number due to heat transfer, N_{S_heat}, versus the fluid behavior index, ω, Nusselt number, Nu, and dimensionless quantity θ_Q: $n = 10$; $m = 2$; Nu = 0.1 (------ $\theta_Q = 0.01$, –..–..– $\theta_Q = 0.10$, –.–.– $\theta_Q = 1.00$, – – – $\theta_Q = 10.00$, —— $\theta_Q = 100.00$).

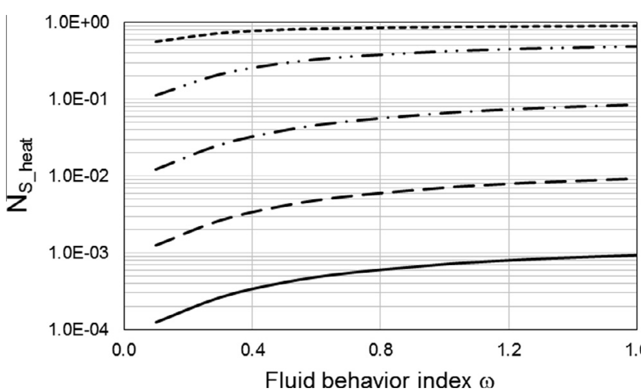

Fig. 2. Entropy generation number due to heat transfer, N_{S_heat}, versus the fluid behavior index, ω, Nusselt number, Nu, and dimensionless quantity θ_Q: $n = 10$; $m = 2$; Nu = 1.0 (------ $\theta_Q = 0.01$, –..–..– $\theta_Q = 0.10$, –.–.– $\theta_Q = 1.00$, – – – $\theta_Q = 10.00$, —— $\theta_Q = 100.00$).

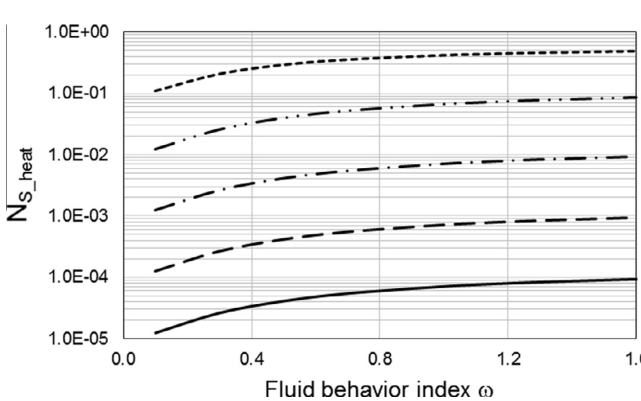

Fig. 3. Entropy generation number due to heat transfer, N_{S_heat}, versus the fluid behavior index, ω, Nusselt number, Nu, and dimensionless quantity θ_Q: $n = 10$; $m = 2$; Nu = 10.0 (------ $\theta_Q = 0.01$, –..–..– $\theta_Q = 0.10$, –.–.– $\theta_Q = 1.00$, – – – $\theta_Q = 10.00$, —— $\theta_Q = 100.00$).

In real flows, not all fluids obey a Newtonian stress–strain relationship: body fluids (e.g., blood) and fluids used in industrial applications often exhibit non-Newtonian (non-linear) behavior

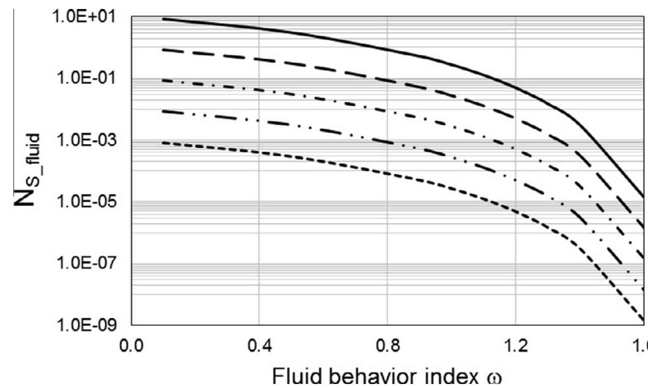

Fig. 4. Entropy generation number due to fluid friction, N_{S_fluid}, versus the fluid behavior index, ω, Metzner–Reed Reynolds number, $Re_{D\omega}$, and dimensionless quantity $\theta_{\phi Q}$: $n = 10$; $m = 2$; $Re_{D\omega} = 0.010$ (———— $\theta_{\phi Q} = 0.01$, –..–..– $\theta_{\phi Q} = 0.10$, –.–.– $\theta_{\phi Q} = 1.00$, – – – $\theta_{\phi Q} = 10.00$, —— $\theta_{\phi Q} = 100.00$).

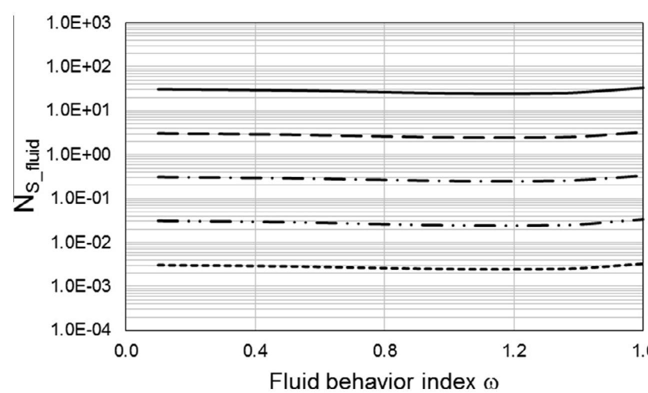

Fig. 5. Entropy generation number due to fluid friction, N_{S_fluid}, versus the fluid behavior index, ω, Metzner–Reed Reynolds number, $Re_{D\omega}$, and dimensionless quantity $\theta_{\phi Q}$: $n = 10$; $m = 2$; $Re_{D\omega} = 0.095$ (———— $\theta_{\phi Q} = 0.01$, –..–..– $\theta_{\phi Q} = 0.10$, –.–.– $\theta_{\phi Q} = 1.00$, – – – $\theta_{\phi Q} = 10.00$, —— $\theta_{\phi Q} = 100.00$).

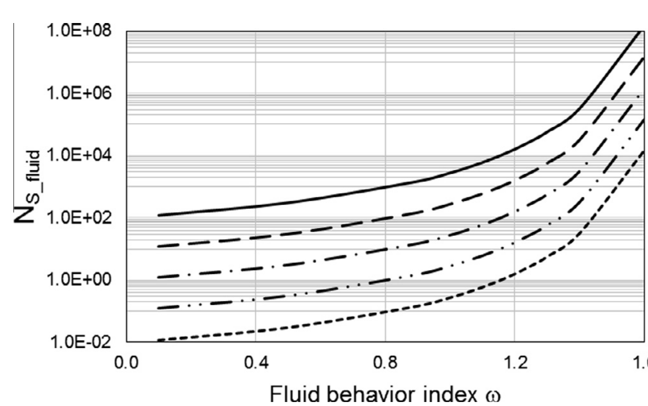

Fig. 6. Entropy generation number due to fluid friction, N_{S_fluid}, versus the fluid behavior index, ω, Metzner–Reed Reynolds number, $Re_{D\omega}$, and dimensionless quantity $\theta_{\phi Q}$: $n = 10$; $m = 2$; $Re_{D\omega} = 1.000$ (------ $\theta_{\phi Q} = 0.01$, –..–..– $\theta_{\phi Q} = 0.10$, –.–.– $\theta_{\phi Q} = 1.00$, – – – $\theta_{\phi Q} = 10.00$, —— $\theta_{\phi Q} = 100.00$).