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# Entropy generation for forced convection in a porous saturated circular tube with uniform wall temperature☆

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**Abstract**

A numerical study is reported to investigate both the First and the Second Law of Thermodynamics for thermally developing forced convection in a circular tube filled by a saturated porous medium, with uniform wall temperature, and with the effects of viscous dissipation included. A theoretical analysis is also presented to study the problem for the asymptotic region applying the perturbation solution of the Brinkman momentum equation reported by (K. Hooman, K., A.A. Ranjbar-Kani, A perturbation based analysis to investigate forced convection in a porous saturated tube, Journal of Computational and Applied Mathematics 162 (2) (2004) 411–419.). Expressions are reported for the temperature profile, the Nusselt number, the Bejan number, and the dimensionless entropy generation rate in the asymptotic region. Numerical results are found to be in good agreement with theoretical counterparts.


*Keywords:* Theoretical; Porous media; Bejan number; Brinkman number; Thermal development

## 1. Introduction

Analysis of fluid flow and heat transfer in porous ducts has been a subject of fundamental importance for being relevant to a lot of industrial applications [2]. There has been a renewed interest in the problem of forced convection through a porous passage for application of hyperporous medium in cooling electronic equipment. Meanwhile a great deal of information is available dealing with, and trying to minimize, the generated entropy due to heat and fluid flow in a porous passage [3–10]. Entropy generation minimization (EGM) is now a popular field of investigation since it aims at minimizing the lost work through decreasing the irreversibility of a system and, hence leads to an optimal design feature. Aiming at this goal, one should find the sources of entropy generation and correlate them with the known and measurable characteristics of the so-called system. One way of tackling the problem is to tie the results of the mass, momentum, and thermal energy balance to the Second Law (of Thermodynamics). Most of the newly-published

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**Nomenclature**

| | |
|---|---|
| Be | Bejan number |
| Be* | average Bejan number |
| Br | Brinkman number |
| Br* | Darcy-Brinkman number |
| $c_P$ | specific heat at constant pressure |
| Da | Darcy number, $K/R^2$ |
| FFI | fluid friction irreversibility |
| G | negative of the applied pressure gradient |
| HTI | heat transfer irreversibility |
| k | effective thermal conductivity |
| K | permeability |
| M | $\mu_{eff}/\mu$ |
| N | dimensionless temperature difference ($N=(T_{IN}-T_w)/T_w$) |
| Ns | dimensionless entropy generation |
| Ns* | average value of Ns |
| Nu | Nusselt number |
| Pe | Péclet number, $Pe=\rho c_p RU/k$ |
| $q''$ | wall heat flux |
| R | Tube radius |
| s | $(MDa)^{-1/2}$ |
| $\dot{S}_{gen}$ | entropy generation rate per unit volume |
| T* | temperature |
| $T_m$ | bulk mean temperature, $T_m = 2\int_0^1 \hat{u}T^* r dr$ |
| $T_w$ | wall temperature |
| u | $\mu u^*/(GR^2)$ |
| u* | filtration velocity |
| $\hat{u}$ | u*/U |
| U | mean velocity, $U = 2\int_0^1 u^* r dr$ |
| x* | longitudinal coordinate |
| x | x*/PeR |
| r* | radial coordinate |
| r | r*/R |

*Greek symbols*

| | |
|---|---|
| $\theta$ | $(T^*-T_w)/(T_{IN}-T_w)$ |
| $\mu$ | fluid viscosity |
| $\mu_{eff}$ | effective viscosity in the Brinkman term |
| $\rho$ | fluid density |

articles follow the methodology of Bejan [11–13] to link the First Law and the Second Law, which assumes two possible sources of entropy generation being Heat Transfer Irreversibility (HTI) and Fluid Friction Irreversibility (FFI). The former is present in almost all of heat transfer devices due to heat transfer in finite temperature differences and the latter is responsible for dissipation of mechanical power to heat (viscous dissipation divided by the local absolute temperature). Modeling viscous dissipation in a porous medium is a controversial issue and there are three alternative models [14–17]. Recently, several authors have investigated the problem for forced convection through a circular tube saturated by a porous medium [18–22]. Hooman and co-workers [18–20] have only considered the Darcy dissipation term and neglected the velocity derivative terms. One knows that this assumption works out when the Darcy number is small [21,d22].