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الجامعة:	جامعة العلوم والتكنولوجيا الاردنية
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ABSTRACT

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Student: Zuhair Nazim A. Musa

Chairman: Dr. Moh'd A. Al-Nimr

This study aims to numerically investigate the transient forced convection in the entrance region of a porous concentric annulus for a non-Newtonian fluid flow. The hydrodynamic behavior of the flow is assumed to be steady. Darcian and non-Darcian effects on the flow are considered in addition to the effect of the power law index which shows the effect of the fluid flow. The governing boundary layer equations have been solved by means of a finite difference scheme. The physical properties of the fluid and the porous medium are considered constant. The thermal boundary conditions are changed in different combinations to form the following four cases:

Case (I): Step temperature change at the inner wall, while the outer wall is kept adiabatic

Case (O): Step temperature change at the outer wall, while the inner wall is kept adiabatic

Case (IE): Step temperature change at both inner wall and entrance cross-section, while the outer wall is kept adiabatic

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The numerical results demonstrate the transient behavior of the temperature profiles, along with the amount of heat absorbed by the flow upon flowing from the entrance cross-section to a certain axial distance. The variation of the thermal entrance length with both Re^* and Da numbers is investigated. Furthermore, the work presents the variation of the mixing cup temperature with time, and the variation of Nusselt number with axial distance. Also, the effect of Prandtl number on both Nusselt number and thermal entrance length is examined.

الخلاصة

العنوان: انتقال الحرارة في السوائل غير النيوتونية السارية في مواد مسامية

الطالب: زهير ناظم أحمد موسى

المشرف: د. محمد النمر

في هذه الدراسة، تم استخدام إحدى طرق الحل العددية (طريقة الفروق المحددة) لحل معادلات الطبقة المتاخمة (الحدية) التي تصف حركة وتوزيع درجات الحرارة للجريان الطباقي (الصفائحي) القسري غير المستقر لسائل غير نيوتوني يمر في وسط مسامي بمنطقة التطور في حيز حلقي بين اسطوانتين مركزيتين، مع ثبات خصائص المائع الفيزيائية وعدم اعتمادها على درجة الحرارة هذا وقد تمت الدراسة عند قيم مختلفة لرقم رينولدز، ورقم دارسي، ورقم براندتل تبعا للحالات التالية:

الحالة الأولى: ويطلق عليها حالة (د) وفيها تم اعتبار الجدار الداخلي عند درجة حرارة ثابتة بينما يكون الجدار الخارجي معزولا.

الحالة الثانية: ويطلق عليها حالة (دم) وفيها تم اعتبار كلا من الجدار الداخلي والمقطع العرضي للمدخل عند درجة حرارة ثابتة ومتساوية مع بقاء الجدار الخارجي معزولا.

الحالة الثالثة: ويطلق عليها حالة (خ) وفيها تم اعتبار الجدار الخارجي عند درجة حرارة ثابتة بينما يكون الجدار الداخلي معزولا.

الحالة الرابعة: ويطلق عليها حالة (خ م) وفيها تم اعتبار كلا من الجدار الخارجي والمقطع العرضي للمدخل عند درجة حرارة ثابتة ومتساوية مع بقاء الجدار الداخلي معزولا.

ولقد تم اعتبار أن سرعة المائع مستقرة نظرا لافتراض أن الخصائص الفيزيائية للمائع لا تتغير مع درجة الحرارة.

وقد عرضت النتائج توزيع درجـات الحـرارة غـير المسـتقر بالإضافـة إلى سـلوك كميـة الحـرارة المنتقلة إلى المائع خلال مسارة من المدخل إلى مسافة ما في الحيز الحلقي وتغيره مع الزمن. ومن ناحية أخرى، فقد تم استنباط تغير الزمن اللازم بوصول المائع إلى حالة حرارية مستقرة مع المسافة وإضافـة إلى ما سبق بينت النتائج تغير درجة الحرارة المتوسطة لخليط المائع مع الزمن.

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NOMENCLATURE

C	Forchheimer constant or porous inertia coefficient, $C = 0.143\varepsilon^{-3/2}$
C_P	specific heat of the fluid (J/kg.K)
Da	Darcy number, $\frac{(K^*/\varepsilon)^{2/(1+n)}}{d_H^2}$
d_H	hydraulic diameter of annulus, $2(r_2 - r_1)$, (m)
g	acceleration due to gravity, (m/s^2)
k	effective thermal conductivity of fluid-saturated porous medium , (W/m.K)
K	intrinsic permeability (m^2) of porous medium
K^*	modified permeability (m^{n+1}) of porous medium for flow of power-law fluids
n	power-law index of inelastic Ostwald-de Waele fluid
N	annulus radius ratio, (r_1 / r_2)
Nu_z	local Nusselt number, $\frac{d_H \left.\frac{\partial T}{\partial r}\right\vert_{wall}}{T_w - T_m} = \frac{1}{1-\theta_m} \left.\frac{\partial \theta}{\partial R}\right\vert_{wall}$
p	fluid pressure at any cross-section
P	dimensionless pressure at any section, $\frac{p - p_o}{\left(\rho/\varepsilon^2\right) u_o^2}$

Pe^* modified Peclet number, $\frac{u_s}{\alpha}\frac{\left(K/\varepsilon\right)^{\frac{n}{2}}}{d_H^{n-1}}$

Pr^* modified Prandtl number, $\frac{Pe^*}{Re_K}$

q_t total heat absorbed by fluid from entrance cross-section until a point under consideration, $2\pi\rho C_P\int_{r_1}^{r_2} r u_s (T - T_o) dr$

Q_t dimensionles heat absorbed by fluid,

$$\frac{q_t}{\pi\rho C_P u_s d_H^2 (T_w - T_o)} = 2\int_{\frac{N}{2(1-N)}}^{\frac{1}{2(1-N)}} RU\theta dr$$

r radial coordinate (m)

r_1 inner radius of the annulus

r_2 outer radius of the annulus

R dimensionless radial coordinate, (r/d_H)

R_1 dimensionless inner radius

R_2 dimensionless outer radius

Re_K Reynolds number for power-law fluid based on length scale,

$$(K/\varepsilon)^{1/2}.\ \frac{\rho\left(K/\varepsilon\right)^{n/2}\left(u_s/\varepsilon\right)^{2-n}}{\mu^*}$$

Re^* microscale Reynolds number based on permeability. $\frac{\rho C K^* u_s^{2-n}}{\mu^*\sqrt{K}}$

t	time (s)
T	temperature (K)
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$T_\circ$	fluid temperature at annulus entrance (K)
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u	axial velocity component (m/s)
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v	radial velocity (m/s)
V	dimensionless radial velocity, $\frac{d_H^2 \mathrm{Re}_K v}{(K/\varepsilon)^{n/2} u_\circ}$
X	volume (m^3)
y	local distance in y-direction coordinate (m)
z	axial coordinate (m)
Z	dimensionless axial coordinate, $\frac{z(K/\varepsilon)^{n/2}}{d_H^{n+1} \mathrm{Re}_K}$

Greek symbols

α	effective thermal diffusivity of porous medium (m^2 / s)

$\dot{\gamma}$	shear rate $\frac{\partial u}{\partial y}$ (s^{-1})
$\ddot{\gamma}$	rate of change of shear rate (s^{-2})
δ	boundary layer thickness (m)
δ_T	thermal boundary layer thickness
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ρ	fluid density (kg /m^3)
	effective heat capacity of the fluid-saturated porous medium $\frac{[\varepsilon\rho C_p + (1-\varepsilon)\rho_s C_{ps}]}{\rho C_p}$

τ	shear stress. (Pa)
τ_1	dimensionless time, $\frac{u_s (K/\varepsilon)^{n/2} t}{\sigma d_H^{n+1} \mathrm{Re}_K}$
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FLUIDS IN POROUS DOMAINS

AT

JORDAN UNIVERSITY OF SCIENCE

AND TECHNOLOGY

Dec, 1996

HEAT TRANSFER OF NON-NEWTONIAN

FLUIDS IN POROUS DOMAINS

BY

ZUHAIR NAZIM A. MUSA

A thesis submitted in partial fulfillment of the requirements of

the degree of Master of Science in

Mechanical Engineering

at

Jordan University of Science & Technology

Dec, 1996

Signature of Author :- ...., 1996

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

There has been a sudden surge of interest in heat transfer in non-Newtonian fluids-saturated porous media. This is because in many engineering applications, a number of fluids exhibiting non-Newtonian behavior come in contact with porous media, particularly in enhanced oil recovery and filtration processes. Further examples of convection of non-Newtonian fluids through porous media may be found in, (1) biomechanics where fluids flow through lungs and arteries. The blood flow is bounded by two layers held together by regularly spaced tissues that are often idealized as porous media, (2) chemical engineering, especially in the case of packed bed reactors, (3) ceramic engineering applications such as drying or burnout of binder system from green compacts during colloidal processing of advised ceramics, and (4) the production of heavy crude oil by means of thermal methods, such as steam injection into oil reservoir.

1.2 Classification Of Non-Newtonian Fluids

Newtonian fluids generally exhibit a linear relationship between shear stress and rate of strain, as shown in equation (1.1). Non-Newtonian fluids exhibit a non-linear relationship between shear stress and rate of strain.

$$\tau = \mu\dot{\gamma} = \mu\frac{\partial u}{\partial y} \qquad (1.1)$$

Metzener [1] classifies non-Newtonian fluids as :

1. Purely viscous
2. Viscoelastic
3. Time-dependent.

Shenoy and Mashelkar [2] classify the non-Newtonian fluids into, namely; inelastic fluids, and viscoelastic fluids.

1. Inelastic fluids

Inelastic fluids are divided into the following groups.

a. Time-dependent

- Thixotropic; exhibit reversible decrease in shear stress with time.
- Rheopectic; exhibit reversible increase in shear stress with time, at a constant rate of shear and fixed temperature.

Time-dependent fluids require extra variables in the governing equations. This makes, the solution process more difficult. Therefore, they are not popular among theoreticians, and for this reason, these fluids have not been considered in heat transfer studies in porous media.

b. Time-independent

- Pseudoplastic fluids: often referred to as shear-thinning fluids. These fluids exhibit a decrease in viscosity with increasing shear rate. Fluids which exhibit this type of behavior include polymer solutions, polymer melts, printing inks, pharmaceutical preparations, and blood. The relation between the shear stress and the rate of strain is shown in equation (1.2)

$$\tau=\mu^{*}|\dot{\gamma}|^{n-1}\dot{\gamma} \qquad n < 1.0 \qquad (1.2)$$

where $\dot{\gamma}=\frac{\partial u}{\partial y}$

- Dilatant fluids: often referred to as shear-thickening fluids. Such fluids exhibit an increase in viscosity with increasing shear rate. Wet sand, starch suspensions, gum solutions, and aqueous suspensions of titanium dioxide are known to show dilatancy. The relation between shear stress and the rate of strain for this type of fluids is shown in equation (1.3)

$$\tau=\mu^{*}|\dot{\gamma}|^{n-1}\dot{\gamma} \qquad n > 1.0 \qquad (1.3)$$

Dilatant fluids are less common than pseudoplastic fluids and dilatancy is observed only in certain ranges of concentration in suspensions of irregularly shaped solids in liquids.

- Bingham plastics: these fluids do not flow unless the applied stress exceeds a certain minimum value, referred to as the yield stress, and then show a linear shear stress versus shear rate relationship as shown in equation (1.4). Systems that show Bingham plastic behavior include thickened hydrocarbon greases, certain asphalts and bitumen, water suspensions of clay, fly ash, mineral, metallic oxides, sewage sludges, jellies, tomato ketchups, toothpastes, and paints.

$$\tau = \tau_Y + \mu_P \dot{\gamma} \tag{1.4}$$

- Pseudoplastic fluids with yield stress have a nonlinear shear stress versus shear rate relationship in addition to a yield stress. This behavior is typical of heavy crude oils with high wax content and shown in equation (1.5)

$$\tau = \tau_y + \mu^* \dot{\gamma}^n \tag{1.5}$$

2. Viscoelastic fluids: these fluids exhibit process properties that lie between those of viscous liquids and elastic solids. Certain amount of energy gets stored in the fluid as strain energy, thereby showing partial elastic recovery upon removal of the deformed stress. Due to the presence of elasticity, viscoelastic fluids show some markedly peculiar steady state and transient flow behavior patterns.

$$\tau + \lambda_{RX} \dot{\tau} = \mu_o (\dot{\gamma} + \lambda_{RD} \ddot{\gamma}) \tag{1.6}$$

The constant λ_{RX} is a relaxation time , that is if motion suddenly stops, the shear stress will decay as $\exp(-t/\lambda_{RX})$. λ_{RD} is called the retardation time and reflects the decay of strain rate as $\exp(-t/\lambda_{RD})$ when all stresses are removed. When λ_{RX} and λ_{RD} are both equal to zero, the model describes a Newtonian fluid .

Finally, the pseudoplastic and dilatant fluids are represented by the Ostwald-de waele power-law model, Bingham plastics by Bingham model, and pseudoplastic fluids with yield stress by Herschel-Bulkley model. In this research, the Ostwald-de waele power-law model is used.

1.3 Modified Forms Of Momentum Equations

Modified forms of momentum equation applicable to non-Newtonian fluids have been obtained through simple mathematical manipulations following procedures analogous to those used in the Newtonian case.

1.3.1 Modified Darcy Law For Power-Law Fluids

Christopher and Middleman [3] were the first to propose the form for Darcy law applicable to power-law fluids.

$$\frac{\mu^*}{k^*}u^n=\rho g-\frac{dp}{dz} \tag{1.7}$$

In using equation (1.7), it is assumed that the flow is slow enough or the pores are small enough to maintain a value of Reynolds number much less than one.

1.3.2 Darcy-Forchheimer Equation For Power-Law Fluids

The validity of the modified Darcy law ceases when the Reynolds number exceeds one. This occurs when flow enters a nonlinear laminar regime at which porous inertia effects have to be considered.

The expression derived by Shenoy [4] can be written as

$$\frac{\mu^* u^n}{K^*} + \frac{\rho C u^2}{\sqrt{K}} = \rho g - \frac{dp}{dz} \tag{1.8}$$

The term $\frac{\rho C u^2}{\sqrt{K}}$ is the same for Newtonian and non-Newtonian fluids, and is basically understood as a porous inertia term that is independent of viscous property effects. C is the inertia coefficient which reflects porous inertia effects (i.e., separation and wake effects).

1.3.3 Brinkman-Darcy Equation for Power-Law Fluids

In the derivation of the Darcy law, only the damping force ($\frac{\mu^* u^n}{K^*}$) is considered and the viscous shear stress acting on the volume element is neglected. This assumption holds good for low permeabilities. However, when the permeability is high, viscous effects must be taken into consideration.

Finally, one can say that when the porous medium has low porosity, and the flow is assumed to be small enough, the modified Darcy law for power-law fluids is applicable.

CHAPTER TWO

LITERATURE SURVEY

2.1 Introduction

Since the early work of Darcy in the 19^{th} century, extensive investigations have been conducted on flow and heat transfer of non-Newtonian fluids through porous media. The literature covers a broad range of different fields and applications, such as, ground-water hydrology, petroleum engineering, ceramic engineering, and thermal insulation.

2.2 Literature Review

An integral solution for the problem of Darcy-Forchheimer natural-convection boundary-layer flow past a semi-infinite vertical flat plate embedded in a power-law fluid-saturated porous medium has been provided by Shenoy [4].

The pure Darcy natural convection boundary-layer problem for flow past an isothermal vertical flat plate embedded in a porous medium saturated with a non-Newtonian fluid has been studied by T. Chen and C. K. Chen [5]. In there work, the authors provided an exact solution for the problem.

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